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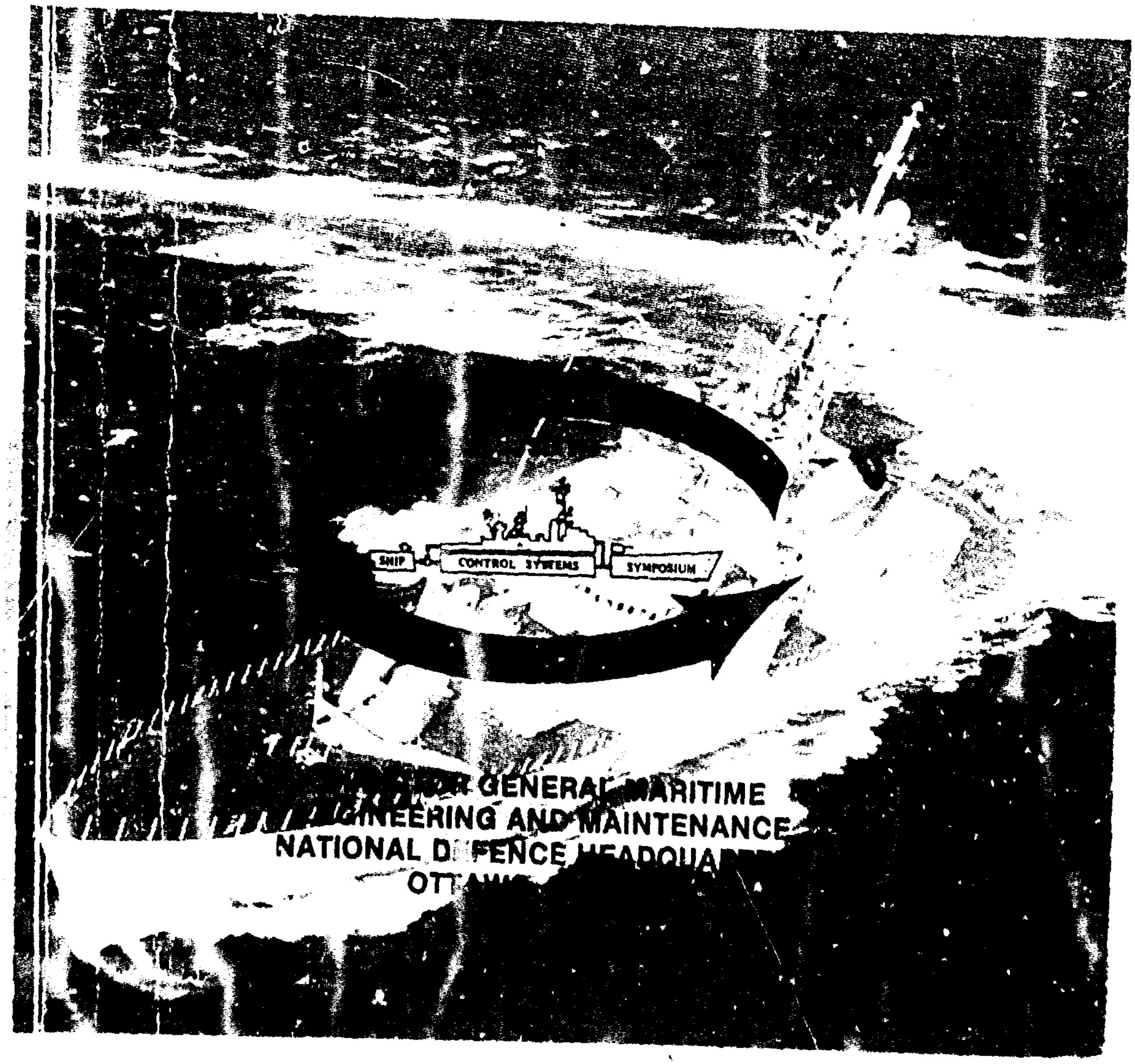

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FOREWORD

The Director General Maritime Engineering and Maintenance (DGMEM) is pleased to present the Proceedings of the Sixth Ship Control System Symposium held at the Chateau Laurier/National Conference Centre complex in Ottawa, Canada, 26-30 October 1981. This is the sixth in a series of symposia on ship control systems. The First Ship Control Systems Symposium was convened in 1966.

The technical papers presented at the Symposium and published in these proceedings cover the entire spectrum of ship control systems and provide an insight into technological developments which are continuously offering the ship control system designer new options in addressing the complex man/machine operation. The microprocessor and its apparently unlimited development potential in future digital, distributed control systems appears ready to reshape the conventional concepts now so familiar in control system designs. There are many concerns that the advantages of the new technologies will be negated by the inability of training systems to graduate technicians who can adequately cope with these new systems.

The response to "Call For Papers" was outstanding and the papers selection committee constrained by the time available for presentations, was hard pressed to make their final selections from the many fine abstracts submitted. The final papers represent a unique international flavour which includes authors from every facet of the ship control system community. The final program is a balance of both theoretical and practical control system papers.

These Proceedings constitute the major record of the Sixth Ship Control Systems Symposium. The contents indicate the success of the Symposium and provide some insight into the effort that was required to ensure this success. The Symposium organizing committee, advisory groups, publications branch, authors, session chairmen, international coordinators, clerical and administrative personnel, and management all provided positive and cooperative support to the many tasks that had to be performed in organizing and presenting the Symposium.

This Symposium has continued to explore and present a number of specific aspects of ship control systems and undoubtly the next symposium will include new concepts and ideas which were unavailable for this Symposium. As in the past, we hope these Proceedings become a source document on ship control along with the previous proceedings. It is our hope that the Symposium has provided stimulation to those who will continue to advance this technical field.

Bruce H. Baxter
General Chairman

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Philip V. Penny
Technical Chairman

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SHIP MOTION CONTROL

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ABSTRACT

In this paper control schemes which are designed to suppress unwanted ship motion, arising from dynamic interaction and sea state disturbances, are investigated. Systematic procedures leaning heavily on computer aided design, harmonic response and multivariable control methods are employed. The mathematical model of the ship system used in the study is derived from measured data from a modern warship which is approximated across a range of speeds to reflect the salient characteristics of the vessel. An integrated scheme of control is proposed which is compensated and connected such that the control surfaces react in a co-operative rather than a competitive manner to enhance, in so doing, the manoeuvring characteristics and general fighting capability of the vessel. Almost as a by-product of the control strategy employed actuator movements are reduced and lower wear and maintenance costs are encountered thereby. The control algorithms used are easily realisable by means of microcomputer software and the predicted response of the system shows that superior seakeeping, than hitherto, may be achieved.

1. INTRODUCTION

During the last decade the problem of ship motion control has been studied with renewed vigour as the requirement for powerful, low cost, low tonnage warships capable of remaining fully operational in adverse weather conditions has increased. The predictable response to this challenge has generally materialised in the form of improved hull and weapon outfits and high power/weight ratio propulsion schemes which are finally assembled to fulfil the fight-float-move function of the lightweight frigate.

Although, enhancing capability in this way may have simple appeal it is expensive and leans heavily upon the assumption that the sub-systems making up the vessel are autonomous whereas in reality they are not. Moreover, the potential of the vessel is never fully realised owing to the use of a piecemeal, rather than an integrated, design approach which ignores the effects of system interaction. Unfortunately, with this structure the suppression of a component of ship motion, using a single sub-system such as stabiliser fins, for example, leads to the simultaneous excitation of secondary response characteristics which are equally undesirable. Thereafter, complicated, competitive control actions are invoked to reduce self induced disturbances thus lowering the performance of the vessel whilst increasing the activity and hence wear on the control system actuators. In contrast an alternative approach whereby roll, yaw and velocity changes are regulated by a co-operative control action, which employs stabiliser fins, rudder and the propulsion

units in concert, offers the prospect of high utilisation, cost effectiveness and superior ship motion and manoeuvring control. Within this scheme the natural cross coupling between outputs would be acknowledged at the outset of the design, enabling the automatic control strategy to produce a smooth, low amplitude, co-ordinated reaction to counter disturbances and enhance the manoeuvring characteristics and general fighting capability of the vessel. Given a rapid turn to execute for example the interactive control scheme would, upon receipt of the helm demand, simultaneously output control commands to the rudders, to the port and starboard shaft sets (in order to achieve differential thrust to assist the turning moment) and at the same time to the stabilisers to counteract the anticipated, induced roll action. Towards completing the turn all of these measures would be gradually relaxed as the new steady state conditions were achieved.

Negotiating a similar manoeuvre with the schemes presently used would, on the other hand, result in the ship heeling, in reaction to the rudder, and the follow through roll condition would then commence. The stabiliser fin servomechanism upon sensing the onset of roll would begin to function after the motion had become established and large corrective movements with consequent heavy power dissipation now becomes necessary. Meanwhile the heel angle induced causes increased fin depression on one side of the ship and elevation on the other, which in turn affects the yaw angle, and hence the ship's heading, so that final corrections via a series of iterative commands, once the turn has been completed, becomes necessary. Of course, if the turn is shallow and it can be performed at low speed then the heel, induced roll and interaction are all small and the additional sophistication in the control scheme is redundant. In tight, high speed manoeuvres however, or in heavy seas, which constitute disturbance inputs on the system, a quiescent platform is highly desirable, especially when preparing weapons or operating aircraft in stress situations. Since an integrated scheme of control would undoubtedly lead to improved stabilisation and manoeuvring characteristics without great capital expenditure or complexity, by better utilisation of the existing propulsion, steering and stabilisation schemes and because lower maintenance effort should also result from the co-operative involvement of the controlled sub-systems, an outline study of the topic is presented here.

2. CONTROL STRATEGY

In order to achieve co-ordinated control, which exploits the naturally occurring interaction in the ship motion dynamics, an integrated design method reflecting the multivariable character of the system must be employed. The need to proceed in this way was recognised by VOZNESENSKII (1938) and more recently ROSENBROCK (1966) who proposed a design method, based on the Inverse Nyquist Array (INA) of the system, which is now quite widely used. The method requires that a pre-compensator achieves, in the combined plant model-compensator inverse, a condition of weakened interaction known as diagonal dominance. If the linearised model of the system is $G(s)$ and the pre-compensator is also an $m \times m$ matrix, $K(s)$, of rational functions, then by definition diagonal dominance ensures that each diagonal element of $(G(s)\ K(s))^{-1}$ exceeds the sum of the moduli of the off-diagonal elements, in the corresponding row or column, for all values of s on the D contour of the s plane. Under these conditions input i to the pre-compensator principally excites output

i from the system for $1 \leq i \leq m$, where m is the number of pre-compensator inputs and system outputs. Consequently, the system when interfaced with this compensator begins to behave as if it were a set of scalar (single input - single output) systems and conventional control system design procedures can now be used. The key to the method resides within the assumption that a proper, realisable, stable K(s) matrix exists, and can be found, with elements in the field of rational functions, such that the INA or alternatively the Direct Nyquist Array (DNA) of the interfaced system model is diagonally dominant. Certainly, for some system models, if K(s) is a matrix of constants, dominance may be accomplished via column operations on G(s) alone. In general however, this kind of good fortune cannot be relied upon especially when there are right-hand plane transmission zeros in the plant model giving rise to non-minimum phase behaviour. Under these circumstances, the systematic procedure outlined in WHALLEY (1978) whereby a decoupling pre-compensator is generated from the spectral form of the transfer matrix, G(s), may be used. Thereafter, simple low order approximations are found such that the compensated system INA or DNA relaxes from non-interaction towards the boundary where diagonal dominance is finally lost. The exchange of compensator complexity against the degree of coupling between outputs is dependent upon the experience and design skill exercised in the manipulation and interpretation of compensator data. Most engineering applications require the use of numerical procedures to accomplish compensator simplification, see for example WHALLEY (1976), and computer aided design with graphical facilities to rapidly examine the dominance condition and hence the relative closed loop stability or gain space of the combined system and compensator. Given for example that:

$$\bar{Q}(s) = (G(s)\ K(s))^{-1}$$

then if

$$\bar{q}_{ii}(s) > \sum_{\substack{i=1 \\ i \neq j}}^{m} \bar{q}_{ij}(s) \qquad j = 1, 2 \ldots\ldots m$$

for all s on the D contour of the s plane, where $\bar{q}_{ij}(s)$ is the i,jth element of $\bar{Q}(s)$, the system is diagonally dominant. Graphically this condition can be quickly identified by plotting $\bar{q}_{ii}(s)$ and superimposing upon this locus circles of radius, $\sum_{\substack{i=1 \\ j=1}}^{m} |q_{ij}(s)|\ i \neq j$

Should any circle intersect the origin of the s plane then dominance has not been achieved and nothing, according to Gershgorin's theorem, can be stated about relative stability under feedback conditions. If however, dominance is maintained then controller design, using the bands swept out by the so called Gershgorin circles, can proceed.

3. SHIP MODEL

In this and subsequent sections measured results from a warship will be used to complete a design - simulation exercise to demonstrate the improvement in sea-keeping available once integrated ship motion controls are employed. As stated earlier a scheme to regulate roll,

heading and velocity changes is to be proposed which employs a control strategy utilising concerted stabiliser, rudder and differential power action. Because of the non-linear dynamic characteristics exhibited measurements at a variety of ship speeds must be collected to cover the operating range of the vessel. Thereafter, separate control scheme designs, having similar structure, so that adaptation in accordance with speed variations can be arrange, should be formulated. In this exercise, since each design follows the same pattern, the ship model at a speed of 12 knots, will be considered.

The least squares fit program (SYSID) of the Imperial College of Science and Technology, University of London, was used to obtain strictly proper, rational function estimates to sea trial data. Slight adjustment of the bias of the estimates towards zero time was necessary to improve the fit, over $0 < t < 20$ seconds, commensurate with third and fourth order denominator polynomials in s. The transfer matrices corresponding to these results are:

$$y(s) = G(s)\, u(s)$$

where:

$$y(s) = (r(s),\ y(s),\ v(s))^t = \text{output vector}$$

$$u(s) = (u(s),\ \beta(s),\ \gamma(s))^t = \text{input vector}$$

with:

$r(t)$ = roll angle change (r_{max} = 15 degrees)

$y(t)$ = yaw angle change (y_{max} = 180 degrees)

$v(t)$ = ship speed change (v_{max} = 36 knots)

$u(t)$ = stabiliser angle change (u_{max} = 25 degrees)

$\beta(t)$ = rudder angle change (β_{max} = 35 degrees)

$\gamma(t)$ = differential power change (γ_{max} = 10%)

and where the elements of G(s) are, for 12 knots:

$$g_{11}(s) = 0.11/(1 + 0.24s + 4.0s^2)$$

$$g_{12}(s) = (-0.09 + 0.8s)/(1 + 9.52s + 17.17s^2 + 53.3s^3)$$

$$g_{13}(s) = g_{21}(s) = 0$$

$$g_{22}(s) = 0.04/(s(1 + 11.2s + 23.25s^2 + 12.0s^3))$$

$$g_{23}(s) = 0.05/(s(1 + 5.0s + 11.2s^2 + 6.0s^3))$$

$$g_{31}(s) = (-\mathrm{sgn}\ u(s))\ (-0.12 - 1.18s)/(1 + 26.0s + 58.0s^2 + 240.0s^3)$$

$$g_{32}(s) = (-\mathrm{sgn}\ \beta(s))(-0.07)/(1 + 34.0s + 240.0s^2)$$

$$g_{33}(s) = 2.66/(1 + 24.0s)$$

and for 18 knots, as shown in Figures 3.1 to 3.7 given overleaf, where the measured and theoretical results are superimposed:

$$g_{11}(s) = 0.18/(1 + 0.24s + 4.0s^2)$$

$$g_{12}(s) = (-0.47 + 4.01s)/(1 + 9.52s + 17.17s^2 + 53.3s^3)$$

$$g_{13}(s) = g_{21}(s) = 0$$

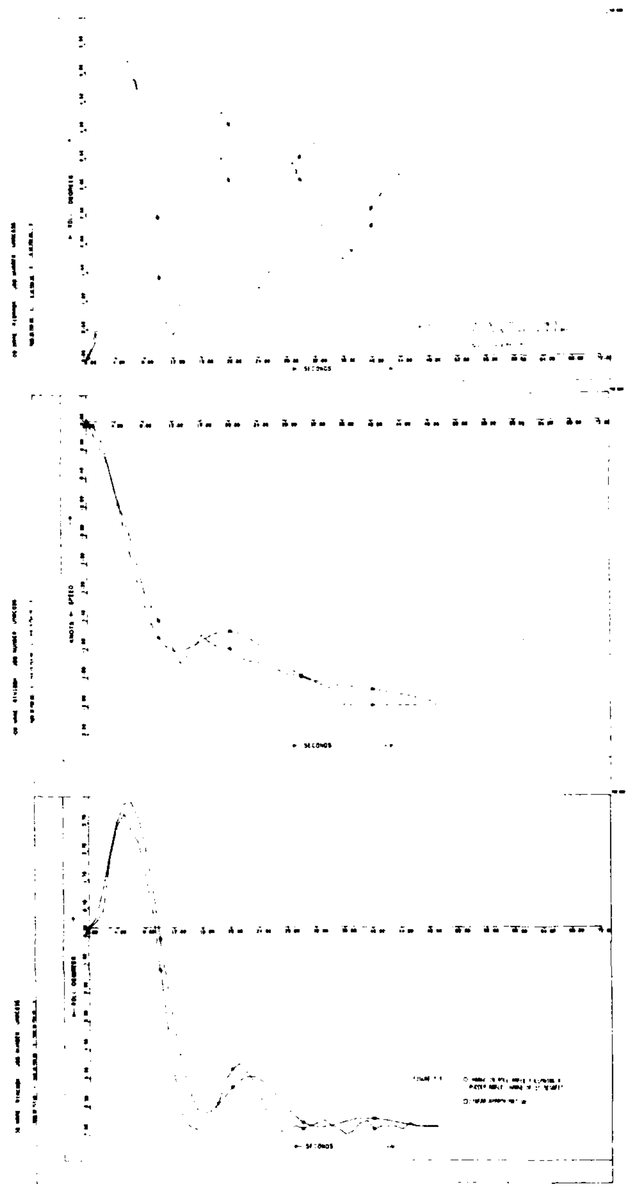
$$g_{22}(s) = 0.08/(s(1 + 11.2s + 23.25s^2 + 12.0s^3))$$

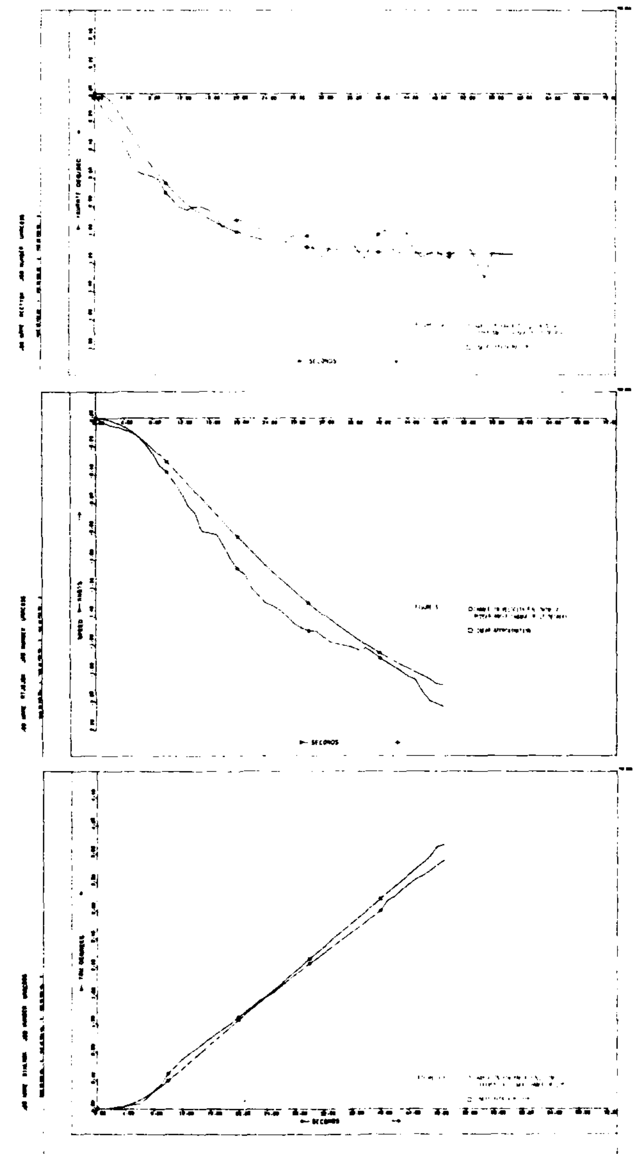
$$g_{23}(s) = .04/(s(1 + 5.0s + 11.2s^2 + 6.0s^3))$$

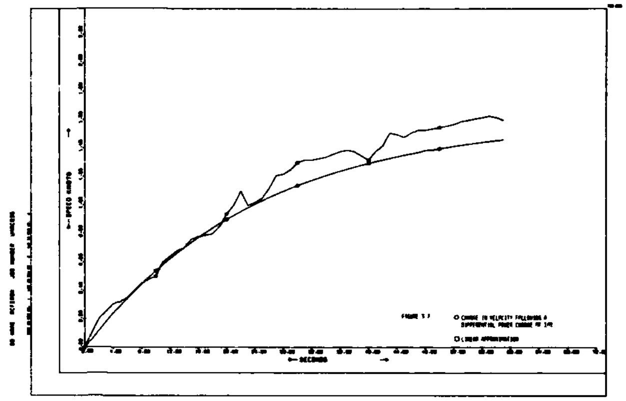
$$g_{31}(s) = (-\mathrm{sgn}\ u(s))(-0.14 - 1.42s)/(1 + 26.0s + 58.0s^2 + 240.0s^3)$$

$$g_{32}(s) = (-\mathrm{sgn}\ \beta(s))(-0.16)/(1 + 34.0s + 240.0s^2)$$

$$g_{33}(s) = 1.58/(1 + 24.0s)$$







4. CONTROL SCHEME DESIGN

It is prudent in all INA or DNA designs to establish first that the plant itself is not diagonally dominant otherwise scalar designs can proceed at once without the troublesome search for pre-compensators to induce this condition. Figure 4.1 and Figure 4.2 show that the ship model at 12 knots is far from being diagonally dominant as the circles representing the off-diagonal elements include the origin of one element, at least, in each case. Following WHALLEY (1978) a decoupling pre-compensator based upon the Spectral Form of G(s) was computed. Reduction of the elements of this compensator, which was exposed to the worst case non-linear condition on elements $g_{31}(s)$ and $g_{32}(s)$, resulted in a final pre-compensator K(s) where the non-zero elements $k_{ij}(s)$ $1 \leq i, j \leq 3$ are:

$k_{11} = 1.20$

$k_{12} = 2.20\ (1 - 8.6s)/(1 + 8.23s)$

$k_{22} = 1.88\ (1 + 1.3s + 6.49s^2)/(1 + 0.24s + 4.0s^2)$

$k_{23} = -0.75$

$k_{33} = 5.0$

The DNA of the system when interfaced with this compensator is given in Figure 4.3 where the Gershgorin bands now exclude the origin thus demonstrating that the dominance condition has been maintained. The effectiveness of the compensator in the time domain is shown in Figure 4.4 to Figure 4.6 where step changes are imposed upon the compensated plant to demonstrate the low degree of interaction which finally exists.

5. SIMULATION

The time domain response of the system under open and closed loop conditions was computed on RNEC's Sigma Six mainframe computer using (CLSIM) the multivariable, non-linear, sample data system software package. The power of this routine is dependent upon the variable step length integration algorithm employed which enables non-linearities to be easily incorporated whilst affording access to the response vector at sub-system intersections. Important information is available from the program on both the output response vector and the corresponding actuator demands which constrain the output characteristics.

This flexibility is fully utilised in the non-linear simulation of the ship motion control problem, following changes in heading demands and roll disturbances, which are shown in Figures 5.1 and 5.2. In the first graph here the output response to an input of 10(1-exp(t/6))%,which is similar to the helmsman's input to the rudder servomechanism, is shown. Very little coupling now occurs at the output restraining loss of speed during the manoeuvre to approximately 1.5% whilst confining heel to less than 0.5%.

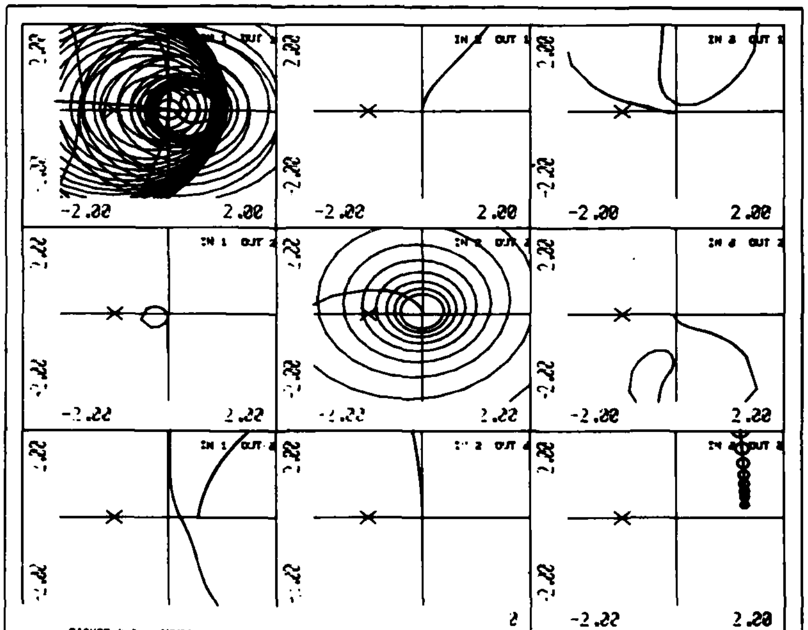


FIGURE 4.1 INVERSE NYQUIST ARRAY OF SHIP MODEL AT 12 KNOTS.
(FREQUENCY RANGE 0.01 TO 6.0 RADS/SEC).

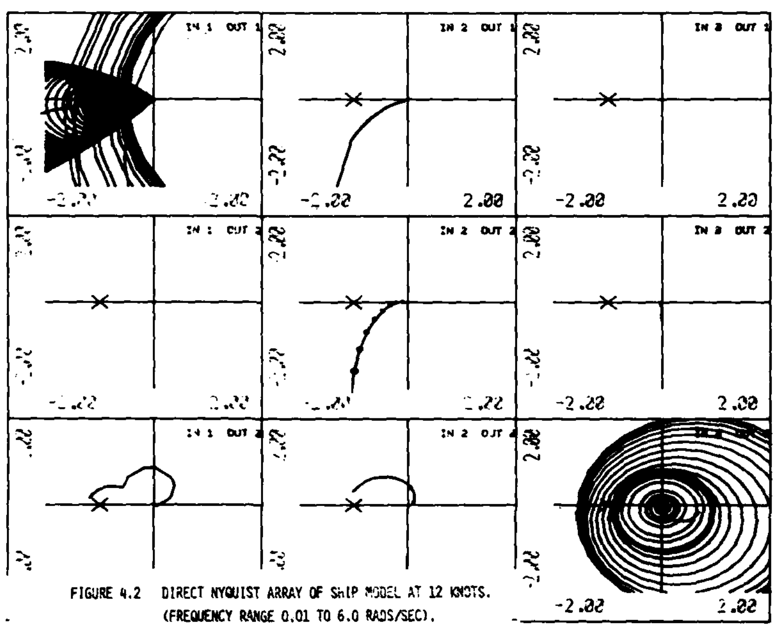


FIGURE 4.2 DIRECT NYQUIST ARRAY OF SHIP MODEL AT 12 KNOTS.
(FREQUENCY RANGE 0.01 TO 6.0 RADS/SEC).

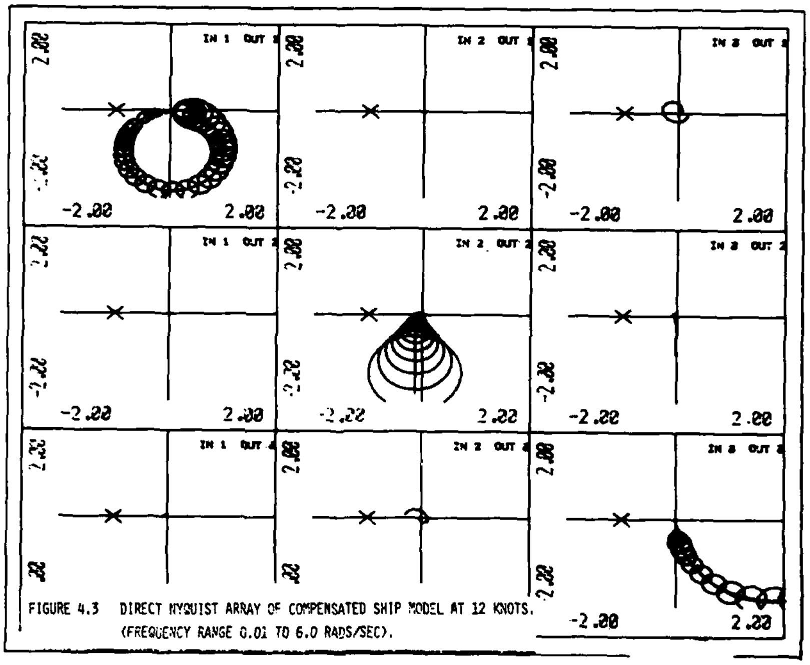


FIGURE 4.3 DIRECT NYQUIST ARRAY OF COMPENSATED SHIP MODEL AT 12 KNOTS.
(FREQUENCY RANGE 0.01 TO 6.0 RADS/SEC).

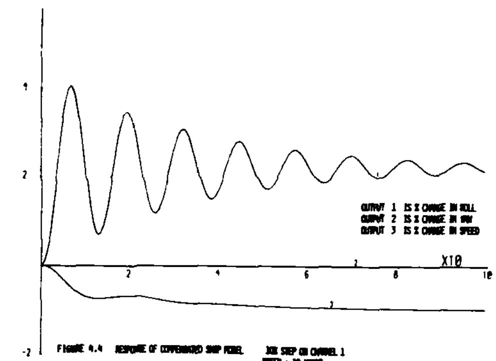


FIGURE 4.4 RESPONSE OF COMPENSATED SHIP MODEL 10% STEP ON CHANNEL 1
SPEED = 12 KNOTS

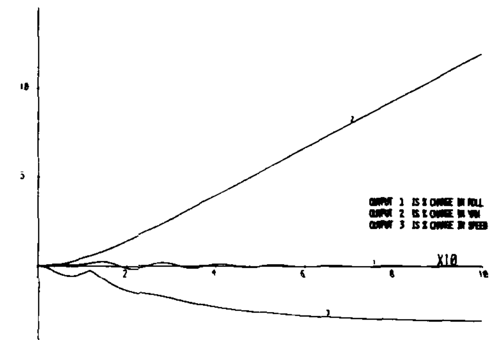


FIGURE 4.5 RESPONSE OF COMPENSATED SHIP MODEL 10% STEP ON CHANNEL 2
SPEED = 12 KNOTS

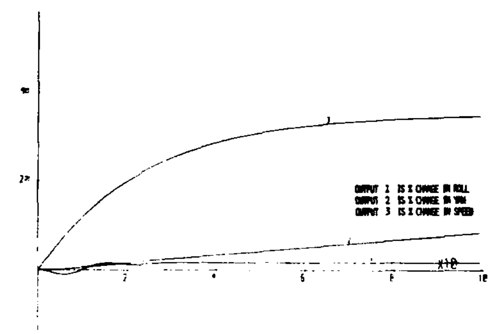


FIGURE 4.6 RESPONSE OF COMPENSATED SHIP MODEL 10% STEP ON CHANNEL 3
SPEED = 12 KNOTS

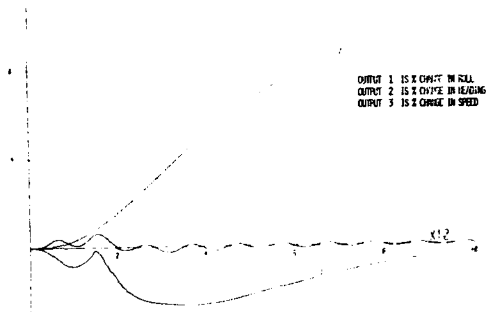


FIGURE 5.1 CLOSED LOOP SIMULATION
GAIN = (5.0, 2.5, 1.0)
INPUT = 10(1 - EXP(- TIME/6))
SPEED = 12 KNOTS

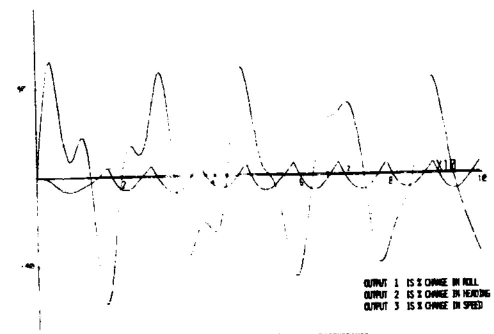


FIGURE 5.2 CLOSED LOOP SIMULATION
GAIN = (5.0, 2.5, 1.0)
INPUT = ROLL DISTURBANCE
= 100% SIN 0.3T
SPEED = 12 KNOTS

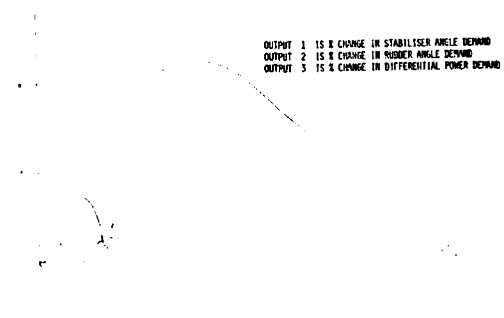


FIGURE 5.3 ACTUATOR ACTIVITY
GAIN = (5.0, 2.5, 1.0)
INPUT = 10(1 - EXP(- TIME/6))
SPEED = 12 KNOTS

Because the pre-compensator ought to reshape and re-order the frequency response loci there should, in well considered designs, be need for little more than proportional feedback to attain closed loop specifications which aim for modest, realisable dynamic improvements. In this case to maintain the ship response to helm changes whilst suppressing roll and speed changes a gain vector of $(5.0, 2.5, 1.0)^t$ has been employed in the error channel.

The actuator activity to achieve this regulation is shown in Figure 5.3. Noticeably, the amplitude of movement demanded of the control actuators is modest as they all contribute to the manoeuvre in a co-operative manner.

Finally to demonstrate that the roll disturbance suppression capacity of the system has not been impaired the response of the vessel in the wake of a periodic disturbance causing a roll of 100% Sin 0.3t was computed. The stabilisers are shown in Figure 5.2 to attenuate the rolling action from an amplitude of 100% to approximately 50% without any appreciable loss of speed or heading which is similar to their performance under autonomous conditions.

6. CONCLUSIONS

The requirements for ship motion and speed control arises from the need to launch and recover aircraft, prepare and deploy weapon and sensor systems such as towed arrays and generally operate a complex vessel in deteriorating weather conditions. Without this sea-keeping ability the efficiency of the most determined crew rapidly deteriorates leaving the most sophisticated warship as it does so, vulnerable to attack. This paper addresses this problem and using multivariable systems theory an integrated scheme of control to enhance the regulation of ship motion is suggested. The system model used was derived from measured results from a modern warship which employed twin screws and two pairs of stabiliser fins. Although the design exercise shown here is focused upon the dynamic characteristics at a speed of 12 knots, models corresponding to other speeds are available enabling a set of related designs to be completed.

The results demonstrate that the ship system outputs of roll, heading and velocity can be controlled using a simple, sparse pre-compensator together with proportional feedback. In constructing this compensator care has been taken to maintain the disturbance attenuating capacity of the roll stabilisers and to limit differential power, which both assists the turning moment and counteracts rudder drag, to 10% for heading changes of approximately 0.33 radians.

In addition to improving the sea-keeping and manoeuvring performance of the vessel the co-ordinated action inherent in the control scheme reduces the actuator power dissipation thus lowering wear and maintenance costs.

Since most modern warships are stabilised, twin screw, rudder steered vessels the scheme discussed here requires the inter-connection of existing sub-systems rather than the addition of new control surfaces to achieve superior sea-keeping and manoeuvring characteristics than hitherto.

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SWATH CONTROL DESIGN USING OPTIMAL TECHNIQUES

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ORI, Inc. and Kathryn K. McCreight,
David W. Taylor Naval Ship Research and Development Center

ABSTRACT

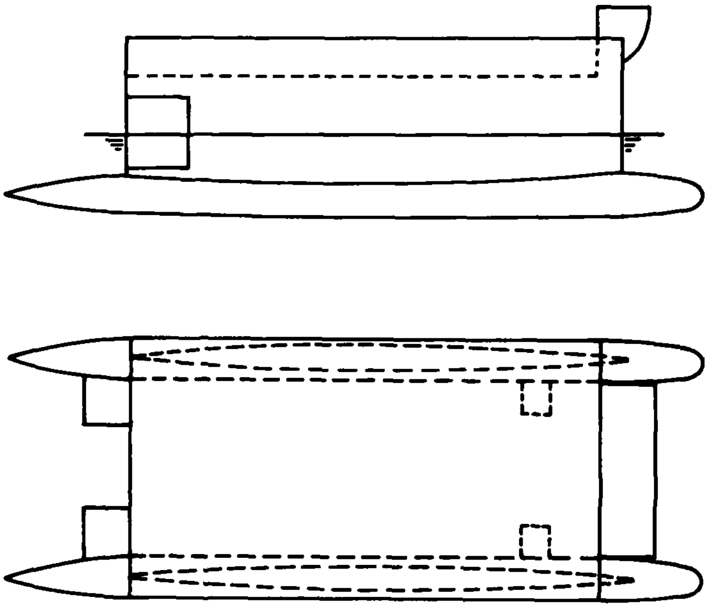
The design of active control systems for SWATH (Small Waterplane Area, Twin Hull) craft is complicated by the frequency dependence of the coefficients in the equations of motion. In addition, if one wishes to evaluate a series of designs in which, for example, fin size and location are varied, a control design technique must be developed which is rapid and leads to consistent results. Consistency of results is extremely important whenever it is necessary to compare various designs with an active controller in the loop as it is possible to find one's self comparing controllers rather than hydrodynamic designs. An optimal control procedure was selected for this application because of the power and flexibility inherent in such an approach. Procedures were developed for both "contouring" and "platforming" control of vertical plane motions (pitch and heave) and evaluated using a time domain simulation at the David Taylor Naval Ship Research and Development Center (DTNSRDC).

INTRODUCTION

The configuration of Small Waterplane Area Twin Hull (SWATH) ships leads to low responses in a seaway and the ability to sustain speed. The SWATH configuration includes two identical lower hulls which are typically slender bodies of revolution. The hulls are separated by a distance on the order of a third or a half of the ship length. These hulls are connected to a deck by one or two surface piercing struts per hull. One SWATH configuration, designated 6A, is shown in Figure 1. The SWATH arrangement results in most of the displaced volume being sufficiently submerged that little wave excitation results. Consequently, in comparison with a conventional ship of equal displacement, a SWATH will have relatively low motions. This, in combination with a relatively large deck area, makes SWATH attractive for use for aircraft operations, weapons firing and sonar towing.

The configuration of SWATH is such that the small waterplane area produces long natural periods with the result that SWATH is not as responsive as a conventional ship to the most commonly encountered seaways. Additionally, the distribution of the waterplane, as reflected in the longitudinal centers of flotation and the longitudinal metacentric height, offers an opportunity to affect seaworthiness. The values of these characteristics affect the heave and pitch natural periods and motion responses and, to some extent, a design can be tuned to the expected seaway and mission requirements.

For high speed missions, stabilizing fins are needed to offset pitch instability, usually two inboard fins per hull. The amount of lift required from each fin is directly related to the desired



Overall Length	73.15m (240.0 ft.)
Strut Length	52.50m (172.3 ft.)
Maximum Strut Thickness	2.21m (7.25 ft.)
Distance Between Centerlines	22.86m (75.0 ft.)
Draft	8.13m (26.67 ft.)
Displacement	2854 tonne (2900 LTSW)
Longitudinal Center of Gravity Aft of Lower Hull Noise	35.45m (116.3 ft.)
Vertical Center of Gravity	10.36m (34.0 ft.)
Longitudinal Metacentric Height	6.10m (20.0 ft.)
Bridging Structure Clearance	6.10m (20.0 ft.)

Particulars of Stabilizing Fins

	Forward m (ft)	Aft m (ft)
Chord	2.59 (8.50)	4.48 (14.7)
Span	3.11 (10.2)	5.36 (17.6)
Maximum Thickness	0.39 (1.27)	0.67 (2.20)
Distance from Nose to Quarter Chord	17.15 (56.25)	62.24 (204.19)

Figure 1. Schematic and particulars of SWATH 6A.

operating speed range because the pitch instability is mostly due to the Munk moment which is proportional to speed squared.

Introduction of well-designed automatic control offers many advantages to SWATH application as compared with the fixed fin case. Automatic control can reduce the size of fins required to offset pitch instability and dampen motions; and as a result, drag is reduced. Automatic control also can serve to improve the seaworthiness of a ship for missions such as aircraft landing and take-off, by maintaining a fixed relationship with an inertial coordinate system (a "platform" mode). For other missions and high sea states platforming may not be acceptable. At high sea states the modal periods of the sea spectra are longer than in lower sea states and thus are apt to be closer to a SWATH's natural periods. If a platforming mode is maintained in high sea states, the deck acts as a limit to what the ship can endure because at some point slamming of the deck will occur. For such conditions, a ship that will follow the wave profile is desireable.

The control system design procedure detailed in the following sections of this paper was motivated by a desire to be able to evaluate various SWATH hull and active fin configurations via a uniform methodology. Linear-Quadratic optimal control theory was selected as the basis for this study because of its adaptability and flexibility as well as the fact that, once properly formulated, it can readily be applied to many craft configurations with little effort.

BACKGROUND

In this paper we will describe the application of Linear-Quadratic (LQ) optimal control theory to the problem of designing active control systems for a SWATH craft in both platforming and contouring modes. The technological event which precipated this effort was the development of a time domain simulation technique for SWATH which permitted accurate controller evaluation. In order to understand the difficulties involved in designing a SWATH controller some knowledge of the history of SWATH simulation is required.

As is common with other surface ships, SWATH has been modeled in the vertical plane by two coupled, second order, ordinary differential equations of the form:

$$A_{33}\ddot{Z} + B_{33}\dot{Z} + C_{33}Z + A_{35}\ddot{\theta} + B_{35}\dot{\theta} + C_{35}\theta = F_3 \qquad (1)$$

$$A_{55}\ddot{\theta} + B_{55}\dot{\theta} + C_{55}\theta + A_{53}\ddot{Z} + B_{53}\dot{Z} + C_{53}Z = F_5 \qquad (2)$$

Where: Z is distance from neutral point, positive upwards
θ is pitch, positive for bow down
F_3, F_5 are sinusoidal inputs
(A_{33}, A_{55} include mass and inertia, respectively)

These equations are valid only when F_3 and F_5 are sinusoidal inputs at the same frequency. The coefficients, A_{ij} and B_{ij} are then functions of the driving frequency. That is, for each driving frequency, the overall craft dynamics appear to change. In order to obtain responses in a realistic seaway it is necessary to approximate the sea spectrum by a sum of sine waves, apply each individually, and apply the super-position principle. Of course this is customarily done via

frequency domain simulation techniques. If the inclusion of an active control system is required then the appropriate frequency domain representation of the compensation is included but this can be a cumbersome procedure especially if the controller has non-linear elements. Additional difficulties arise due to the non-linearities in the active fin systems, primarily position and rate limiting. While it is possible to include these effects via appropriate describing function techniques these can be extremely complex and subject to inherent inaccuracies. To mitigate this problem Livingston (ref. 1) suggested rewriting equations (1) and (2) in the transfer function form:

$$Z = H_{33}(j\omega)F_3 + H_{35}(j\omega)F_5 \tag{3}$$

$$\theta = H_{53}(j\omega)F_3 + H_{55}(j\omega)F_5 \tag{4}$$

Where: $j\omega$ is the complex frequency

in which the H_{ij} are frequency domain fits in the region of interest.

The H_{ij} of equations (3) and (4), which describe the heave and pitch motions of SWATH, can be simulated easily in the time domain and the non-linearities necessary to complete the modeling of the ship's motions are easily included. The result is a time domain simulation which reproduces the results of the frequency domain approach but has the decided advantage that non-linearities can be included with an ease and accuracy that is not possible with describing function techniques. This simulation is then the tool by which the control designs can be evaluated.

Despite the advantages of the transfer function formulation for simulation purposes, it precludes the application of Linear-Quadratic (LQ) theory for several reasons. In order to understand this we will provide the basic results of LQ theory at this point and refer the reader to standard sources (see, e.g., references 2 and 3) for further explanation. The LQ control problem is to find a control u such that the performance functional:

$$J = E\left\{ x^T Q x + u^T R u \right\} \tag{5}$$

is minimized subject to the constraints imposed by the linear, ordinary, differential equations:

$$\dot{x} = Ax + Bu \tag{6}$$

Where: E is the expected value (averaging operator)

x is a vector of dynamic variables, referred to as the system "state".

u is a vector of controls

Q and R are suitably dimensioned weighting matrices, positive and positive definite, respectively.

A is a matrix describing the system dynamics

B is a matrix relating the controls to the system state derivatives.

T is used to denote the transpose of a vector or matrix.

The reason why the form of Equation (5) is called "quadratic" can be seen from the simple case in which both Q and R are diagonal matrices (with positive elements). In this circumstance the resulting performance functional is the weighted sum of the mean square value of the states and the controls. The solution of Equations (5) and (6) is that the optimal control is;

$$u = -Gx \tag{7}$$

with;

$$G = R^{-1}B^{T}K \tag{8}$$

and K is the symmetric, positive definite solution of the matrix Ricatti equation:

$$A^{T}K + KA + Q - KBR^{-1}B^{T}K = 0 \tag{9}$$

Each variable whose derivative appears on the left hand side of Equation (6) is referred to as a "state variable" and the form of Equation (6) is called the state variable formulation.

As can be seen from Equation (7), the optimal control is a weighted sum of the states. If the simulation Equations (3) and (4) were written in state variable format the order of each would be the sum of the orders of the denominator of the transfer functions and the full state feedback required by Equation (7) would be extremely cumbersome as well as unrealistic in terms of the high order derivatives of heave and pitch required.

In order to investigate alternative approaches we must put the SWATH equations of motion, Equations (1) and (2) in state variable format. Including the forces and moments from the active fins fore and aft these become:

$$A_{33}\ddot{z} + A_{35}\ddot{\theta} = -B_{33}\dot{z} - C_{33}z - B_{35}\dot{\theta} - C_{35}\theta + b_{11}d_F + b_{12}d_A + F_3 \tag{10}$$

$$A_{53}\ddot{z} + A_{55}\ddot{\theta} = -B_{53}\dot{z} - C_{53}z - B_{55}\dot{\theta} - C_{55}\theta + b_{31}d_F + b_{32}d_A + F_5 \tag{11}$$

Where: d_F is the deflection of the forward fin
d_A is the deflection of the aft fin

$$\begin{bmatrix} A_{33} & 0 & A_{35} & 0 \\ 0 & 1 & 0 & 0 \\ A_{53} & 0 & A_{55} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \ddot{z} \\ \dot{z} \\ \ddot{\theta} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -B_{33} & -C_{33} & -B_{35} & -C_{35} \\ 1 & 0 & 0 & 0 \\ -B_{53} & -C_{53} & -B_{55} & -C_{55} \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{z} \\ z \\ \dot{\theta} \\ \theta \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ 0 & 0 \\ b_{31} & b_{32} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} d_F \\ d_A \end{bmatrix} + F \qquad (12)$$

This can be more simply written as:

$$T\dot{x} = A_1 x + B_1 u + F_1 \qquad (13)$$

where the definition of the vectors and matrices is evident. The final step required to put this into proper format for LQ theory application is to pre-multiply by T^{-1}:

$$\dot{x} = T^{-1}A_1 x + T^{-1}B_1 u + T^{-1}F_1 \qquad (14)$$

or: $\dot{x} = Ax + Bu + F$ (15)

where, once again, the definition of the matrices is evident. (Note: In some of the ensuing discussions we will ignore the influence of the forcing function vector, F, on the control system design. This decision is only partially rooted in the separation theorem of optimal control. The full explanation can be found in Reference 4).

The open loop stability of the SWATH can be studied by considering the eigenvalues of the matrix A in Equation (15). These are shown as a function of frequency in Figure 2 across the frequency range of interest. Figure 2 shows a significant migration of the eigenvalues thus implying that the frequency dependence is substantial and cannot simply be ignored in the analysis. However, it is encouraging to find that the eigenvalues associated with height which are lightly damped, do not show great movement; while those associated with pitch, which do show considerable movement, appear to be fairly well damped.

Having established that the frequency dependence of the coefficients of the SWATH system cannot simply be ignored in the control design, we must determine a technique that will result in good response in the desired frequency range. While several potential design techniqes could have been employed, the one that was selected was prompted by the desire to increase the relatively low heave mode damping. Because the response of lightly damped systems is considerably amplified in the vicinity of the natural frequency and differs little from well damped system response elsewhere, we elected to design an optimal LQ system using the coefficients for which the disturbance frequency corresponds to the open loop natural heave frequency. For the SWATH 6A this was 0.680 radians per second.

Figure 3 shows the closed loop eigenvalues for a typical design. As expected, heave stability is significantly improved and the SWATH will exhibit good stability characteristics at all frequencies of disturbance.

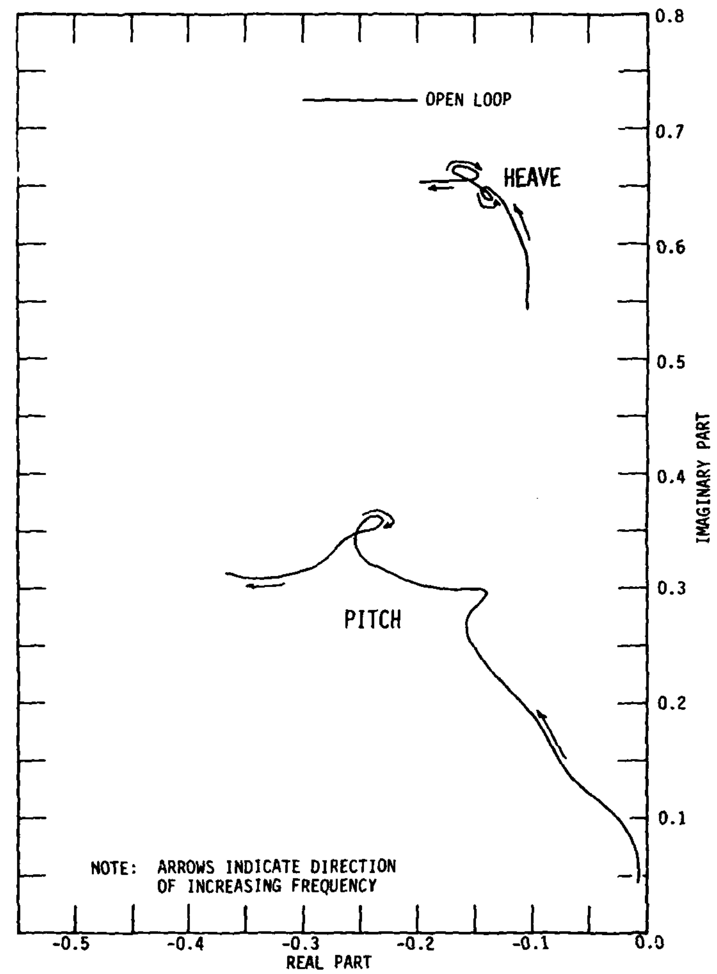


Figure 2. SWATH 6A Open Loop Eigenvalues at 20 Knots as a Function of Forcing Frequency from 0.0425 to 1.700 Rad/Sec.

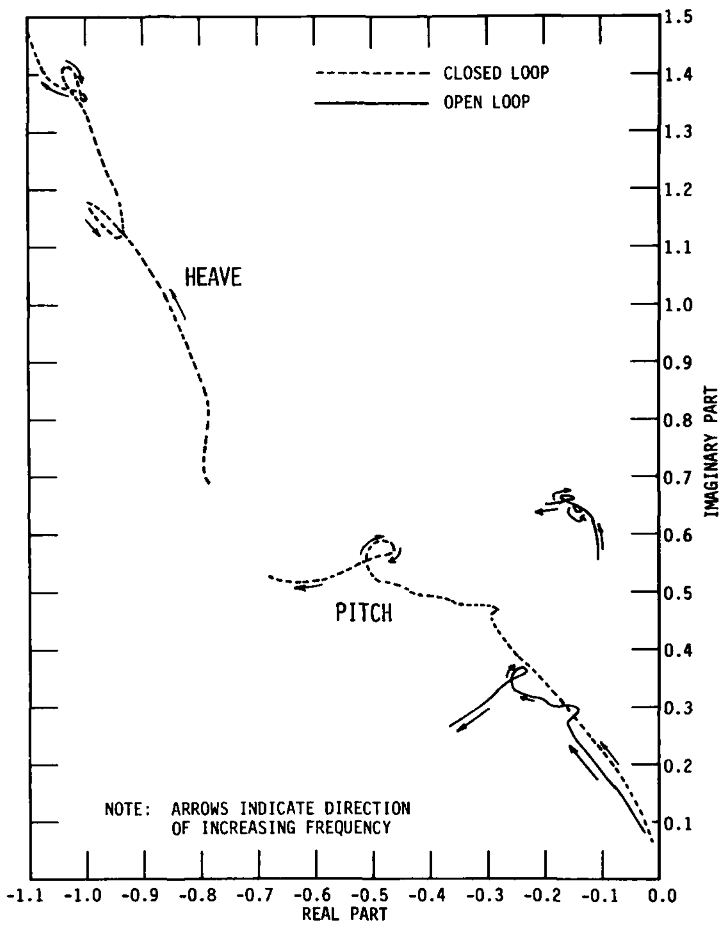


Figure 3. SWATH 6A Open and Closed Loop Eigenvalues as a Function of Forcing Frequency from 0.0425 to 1.700 Rad/Sec.

PLATFORMING VERSUS CONTOURING

As mentioned earlier, the SWATH is expected to operate in either of two modes: platforming or contouring. Because in the platforming mode the ship is expected to remain more or less fixed with respect to an inertial reference frame, the previously expressed state formulation is sufficient. However, in the contouring mode the craft is expected to conform to the local wave surface. By doing this impact loads and deck wetness will be reduced. An indicator of contouring performance is the "relative bow motion" which is the motion of some point on the craft near the bow with respect to the wave surface at that point. Thus a useful measure of contouring performance would be the variance (or, equivalently, the standard deviation) of the relative bow motion, i.e.:

$$J = E\left\{((Z_b - \eta_b) - E\{(Z_b - \eta_b)\})^2\right\} \qquad (16)$$

where: J is the performance measure to be minimized.

Z_b is the motion of a point on (or near) the bow relative to an inertial reference frame.

η_b is the wave height at the point at which Z_b is measured.

This expression for a performance criteria does not fall within the LQ framework because the variable is not a state within the previously defined framework of equations. We would like to write the previous dynamic equation, Equation (15), with a new state corresponding to relative bow motion. To do this we note that:

$$Z_b = Z - L_b \sin(\theta) \qquad (17)$$

where: L_b is the distance from the CG to the point of measurement, positive forward.

Using the small angle approximation for the pitch angle, we can write a new state definition as follows:

$$\left|x_b\right| = \begin{bmatrix} \dot{Z}_b - \dot{\eta}_b \\ Z_b - \eta_b \\ \dot{\theta} \\ \theta \end{bmatrix} = \begin{bmatrix} 1 & 0 & -L_b & 0 \\ 0 & 1 & 0 & -L_b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{Z} \\ Z \\ \dot{\theta} \\ \theta \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\eta}_b \\ \eta_b \end{bmatrix} \qquad (18)$$

or

$$x_b = Tx + Ew \qquad (19)$$

Rearranging:

$$x = T^{-1}x_b - T^{-1}Ew \tag{20}$$

Substituting Equation (20) into Equation (15) will yield a new matrix differntial equation with the required states.

$$\dot{x}_b = TAT^{-1}x_b + TBu + (E\dot{w} + TF - TAT^{-1}Ew) \tag{21}$$

Equation 21 can be re-written by simple redefinition of matrices as:

$$\dot{x}_b = A_b x_b + B_b u + F_b v_b$$

Thus it has been demonstrated that the contouring problem is amenable to the LQ control approach. Once again we choose to ignore the noise states for the reasons detailed in Reference 4.

INTRODUCTION OF CONTROL RATE WEIGHTING

Because the hydraulic systems used for moving the fins are rate limited we would like to include a weighting on control rate in the quadratic performance functional. That is:

$$J = E\{x^T Q x + u^T R u + \dot{u}^T N \dot{u}\} \tag{22}$$

Where: $\dot{u}$ is the vector of control rates

N is the matrix of control rate weightings.

This is easily done by defining a new state, x_1, as:

$$x_1 = \left| x \ , \ u \right|^T \tag{23}$$

and a new control:

$$u_1 = \dot{u} \tag{24}$$

By redefining the system matrices as follows:

$$A_1 = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \tag{25}$$

$$B_1 = \begin{vmatrix} 0 \\ I \end{vmatrix} \tag{26}$$

$$Q_1 = \begin{bmatrix} Q & 0 \\ 0 & R \end{bmatrix} \tag{27}$$

$$R_1 = N \tag{28}$$

the rate weighting can be included in the standard LQ format. The solution is:

$$u_1 = \dot{u} = -G_1 x_1 \tag{29}$$

which can be partioned as:

$$\dot{u} = -G_x x - G_u u \tag{30}$$

or:

$$u = (Is + G_u)^{-1}(-G_x x) \tag{31}$$

Where: I is the identity matrix

s is the Laplace transform variable.

(N.B. The preceeding steps ignore a subtlety with regard to the feedback of u for control. However, in most practical applications this procedure is valid.)

For a single control the inclusion of control rate weighting introduces a first order (low pass) filter into the control loop which serves to attentuate high frequency effects. In a multiple control environment, such as the case with SWATH, the practical implementation of Equation (31) can be awkward due to the cross coupling between the controls introduced by the matrix, G_u. Fortunately in many practical cases, including SWATH, the matrix G_u is strongly diagonal and the cross coupling can be ignored without noticeable degradation in overall performance of stability. It is important to check the resulting stability to insure that only a small degradation has occurred by computing the eigenvalues of the resulting closed loop matrix:

$$A_{CL} = \left[\begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} - \begin{bmatrix} 0 \\ I \end{bmatrix} \begin{bmatrix} G_x & \mathrm{Diag}(G_u) \end{bmatrix} \right] \tag{32}$$

SIMULATION RESULTS

Selecting the elements of the weighting matrices, Q_1 and R_1, completes the control system design procedure. This selection is dictated by engineering judgement, knowledge of system dynamics, and experience in dealing with LQ designs. The fact that the SWATH system, as do all real systems, deviates in many ways from the LQG assumptions makes selecting these weightings more of an art than a craft and much

could be written about these procedures. One simple approach that often gives good results, or at least a good starting point, is to select a set of acceptable deviations in the state and control variables and select the appropriate diagonal elements of the weighting matrices to be the square of the reciprocal of these deviations with all off-diagonal terms set to zero. We selected the following deviations:

D_z = 4 feet

D_θ = 2 degrees (corresponding to a motion of 4 feet at half the craft length from the CG.)

$D_{\dot{z}}$ = 0.2 feet/sec. (to obtain additional damping in heave)

$D_{dF,dA}$ = 10 deg. (one-half the maximum deflection of the forward and aft fins)

$D_{d\dot{F},d\dot{A}}$ = 7.5 deg./sec. (one-half the maximum rate)

Simulations demonstrated that these were good weightings for platforming conditions but that they resulted in excess fin motions during contouring runs. Sensitivity studies showed that a better set of weightings for contouring in Sea State 6, the design condition, would be obtained by decreasing the allowable fins motions by selecting:

$D_{dF,dA} = D_{d\dot{F},d\dot{A}}$ = 1 deg. or deg./sec.

Using the control system parameters generated from the weightings shown above, the results shown in Table 1 were obtained. This table presents the standard deviations of motion variables of primary interest for the SWATH 6A operating in head seas for both Sea State 5 ($H_{1/3}$ = 10 feet) and Sea State 6 ($H_{1/3}$ = 15 feet) for a speed of 20 knots. For comparison purposes, the zero gain condition in which no motion of the active fins occur, is also presented.

The platforming condition shows the most remarkable improvement with CG motion reduced by a factor of 3 or greater (3.13 in Sea State 5 and 3.55 in Sea State 6). The improvement in pitch motions is not as dramatic but the pitch motions were not substantial in the no-control case. This result could have been anticipated as the damping in heave without active control was very small, the damping ratio being about 0.23 around the frequency of interest. Thus simply increasing the damping ratio by including gains on heave rate caused a large performance improvement.

The performance improvement in the contouring case (as evidenced by relative bow motion, Z_b) is much less than in the platforming case. This, too, was anticipated as to reduce relative bow motion requires that the ship respond to fairly high frequency inputs caused by wave height sensing. The peak of the encounter frequency in Sea State 6 is

Table 1. Platforming and Contouring Performance for SWATH 6A in Head Seas at 20 Knots

Condition	Variable	Standard Deviation: Sea State 6 $H_{1/3}$ - 15 ft.	Standard Deviation: Sea State 5 $H_{1/3}$ - 10 ft.
Zero Gains	z_i	2.251	.702
	θ	.708	.368
	$\ddot{z}_i$	1.476	.666
	$z_b-\eta$	5.320	3.459
	dF	0.	0.
	dA	0.	0.
	$d\dot{F}$	0.	0.
	$d\dot{A}$	0.	0.
Platforming	z_i	.633	.226
	θ	.545	.326
	$\ddot{z}_i$	.565	.382
	$z_b-\eta$	5.161	3.298
	dF	4.681	3.144
	dA	4.609	2.909
	$d\dot{F}$	4.189	2.277
	$d\dot{A}$	4.609	2.071
Contouring	z_i	2.185	.779
	θ	1.173	.660
	$\ddot{z}_i$	1.628	.817
	$z_b-\eta$	4.114	3.129
	dF	5.885	5.595
	dA	6.499	4.927
	$d\dot{F}$	3.882	2.936
	$d\dot{A}$	5.288	3.361

approximately 0.95 radians/second. Relative bow motion is reduced by about 23% in Sea State 6 but virtually unchanged in Sea State 5. Fin motions are quite small in Sea State 5 indicating that it might have been possible to decrease the weightings on fin activity for the lower sea state which may have resulted in increased performance. However, sensitivity of performance to changes in weighting is not high and it may be that little improvement is possible.

SUMMARY

We have demonstrated the utility of an optimal control approach for the design of active control systems for the SWATH craft. While this by no means solves all of the problems of SWATH motion control it does allow the designers to proceed in a rational manner for evaluating various hydrodynamic and hardware factors such as fin shape, fin size, hull and/or strut design, maximum fin deflection, and maximum fin rates. Using an optimal control theoretic approach designers can perform sensitivity and trade-off studies with an ease and confidence not heretofore possible.

ACKNOWLEDGEMENT

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A POTENTIAL CONTROL ELEMENT FOR ADVANCED SHIPS

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ABSTRACT

A variety of advanced ship designs include a need to maintain precise height or altitude with respect to the ocean's surface. Individual requirements are to control ride height, ride quality, or ship stability. In other instances designers would like to provide a detailed description of the ocean's surface in order to provide greater precision in the evaluation of various control elements and ship systems. A sensor or control system capable of measuring wave height and converting it to a control signal is thus highly desirable as a ship control element.

This paper describes the development of the initial elements of one such system intended for eventual use in the ride control systems of surface effect ships. The heart of the system is a wave-profile measuring unit consisting of a strapdown inertial sensor package, radar or laser altimeter, and associated electronics. The inertial package includes a separate vertical gyroscope located near the ship center of gravity and an accelerometer triad located at the altimeter site. The electronics unit combines inertial, altimeter and ship-speed signals to compute the motion of the ship and altimeter. These computed motions are subtracted from the altimeter-measured wave height signal to yield a real-time description of absolute wave height. These data along with ship inertial data thus provide the fundamental elements of a control feedback signal. The implementation of the current inertial package and sensor are discussed and the performance of the system in at-sea tests is given. The limitations that various sensors imply for the use of the system as a control element are indicated.

INTRODUCTION

Various applications exist in which it is required to precisely measure the distance from some reference point to the sea surface. Such data have been used in hydrofoils to maintain constant foil immersion and are currently being considered for application in Ride Control Systems(1) of Surface Effect Ships. A system capable of providing this information would also be capable of measuring wave height and sea state. These latter data are potentially useful for evaluating insurance claims and for test and evaluation purposes. Waverider buoys and Wavestaffs are commonly used for determining wave spectra near a fixed point but use of such data requires statistical inference when applied to the evaluation of non-local or moving ships. Tuckermeters(2) provide wave spectra by sensing water pressure variations caused by changing surface conditions. The

Tuckermeter is limited in frequency response, and requires recalibration for each wave frequency, ship speed and depth.

A more attractive procedure is to provide an acoustical, laser or radio sensor which measures distance using radar principals. The principals of such sensors are well understood and radio altimeters are commonly used to measure height over a wide variety of ranges in commercial aircraft. Since both the ship and the altimeter package can be in motion, another sensor, an inertial reference, is required to be able to convert measured wave height to absolute wave height. In the current application (See Figure 1.) this has been accomplished by affixing an accelerometer triad to the sensor package which is in turn mounted to the ships bow by a rigid beam. The sensor package thus has a clear view of the undisturbed sea surface ahead of the ship. A second inertial package located near the ships center-of-gravity provides data on the ships motion. An electronics unit or computer combines the outputs of the ship and sensor inertial packages to compute the motions of the altimeter and these motions are in turn subtracted from the radar range data to determine wave height.

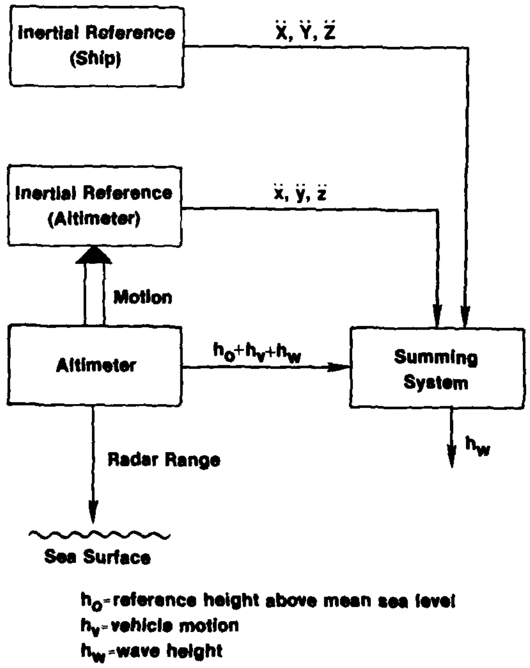

Figure 1. Basic System for Establishing Range to Sea Surface and Correcting for Sensor Motion.

Several agencies have been involved in one or more phases of this development. The Applied Physics Laboratory, Johns Hopkins University (APL) integrated the inertial reference into the total sensor package and performed feasibility studies on laser altimeters. The Naval Research Laboratory (NRL) conducted analysis to determine the fundamental factors limiting system accuracy and performed feasibility tests on pulsed radars. The Surface Effect Ship Project (PMS 304) provided at-sea and model experience using a variety of special purpose sensors developed for ship speed measurement and various Test and Evaluation projects.

INERTIAL REFERENCE

Again referring to Figure 1, the wave profiling system consists of two fundamental parts, the altimeter or range sensor package and the inertial reference. The latter is used to correct the measured radar range for the motion of the altimeter and the ship in order to provide absolute wave height. Such a system is straight forward but reasonably complex to implement in practice. As part of its effort to develop the inertial reference, APL[3] developed a unique coordinate transformation which greatly simplified the transformation required for correcting the altimeter outputs for sensor motion.

Referring to Figure 2 it can be seen that the altimeter output, E_o, is the sum of three outputs: one due to the mean wave height, h_o, one due to vehicle motion, h_v, and one due to the movement of the surface itself, h_w:

$$E(t) = h_o + h_v(t) + h_w(t). \qquad (1)$$

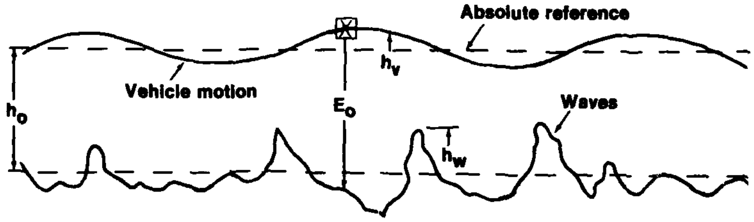

Figure 2. Geometric Relationship of Vehicle Borne Altimeter Measuring Range to Sea Surface.

In order to obtain the desired wave height measurement, h_w, it is thus necessary to correct the sensor output for ship motions. In practice this has been done by installing an accelerometer triad at the sensor location, and a vertical gyroscope near the ships center of gravity. The procedure is then to measure the total acceleration using the vehicle mounted accelerometer triad and to transform these measurements to the local vertical reference near the center of gravity. Finally a double integration is performed to convert

vertical acceleration to vehicle displacements. The acceleration transformation is described by:

$$A_i = \sum_j M_{ij} B_j \tag{2}$$

where the local acceleration matrix A is described in terms of ship acceleration $\ddot{X},\ddot{Y},\ddot{Z}$, and the triad accelerometer acceleration matrix B is described in terms of altimeter accelration $\ddot{x},\ddot{y},\ddot{z}$. The coordinate transformation matrix M, in terms of ordered angular motions in heading, Ψ, pitch, θ, and roll, φ, is given by:

$$[M] = \begin{bmatrix} \cos\theta\cos\Psi & (-\sin\Psi\cos\phi+\cos\Psi\sin\theta\sin\varphi) & (\sin\Psi\sin\varphi+\cos\Psi\sin\theta\cos\varphi) \\ \sin\Psi\cos\theta & (\cos\Psi\cos\varphi+\sin\Psi\sin\theta\sin\varphi) & (-\cos\Psi\sin\varphi+\sin\Psi\sin\theta\cos\varphi) \\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi \end{bmatrix} \tag{3}$$

which results in a vertical acceleration:

$$\ddot{z} = -\ddot{x}\sin\theta + \ddot{y}\cos\theta\sin\varphi + \ddot{z}\cos\theta\cos\varphi. \tag{4}$$

Although straight forward, the implementation of equation (4) in hardware leads to certain difficulties. It was observed by APL that the roll and pitch attitude of the SES were relatively small (typically less than plus or minus 10 degrees). Further they determined empirically and through careful error analysis that for those conditions prevailing on the SES the substitution:

$$\ddot{z} = \frac{-\ddot{x}}{2}\sin\theta + \frac{\ddot{y}}{2}\sin\varphi + \ddot{z} \tag{5}$$

should result in a maximum error of approximately 0.03 percent of measured wave height. This substitution greatly simplifies the electronics required to implement the transformation.

Considerable care is also required in implementing the double integration which converts acceleration to displacement. The time constant for waves is such as to create problems with both data cut-off frequency and instability. Equation (4) is an exact equation for vertical acceleration in terms of body sensed acceleration $(\ddot{x},\ddot{y},\ddot{z})$ and associated body attitude (φ,θ); however, when a "real world" model of an accelerometer is substituted in the equation it becomes evident that "dc offsets" due to tilt, misalignment, etc. can contribute to significant errors. For instance, when the accelerometer measurement includes a small dc offset, a_o:

$$\ddot{z} \simeq a_o + \ddot{h} \tag{6}$$

and if θ and φ are very small:

$$\ddot{z} \simeq \ddot{z} = a_o + a_1 \ddot{h} \tag{7}$$

and hence:

$$z(t) \simeq \frac{a_o t^2 + h(t)}{2} \tag{8}$$

which can lead to significant errors even for very small offsets. The desire to eliminate these offsets as well as electronic noise leads to the introduction of various low pass, α_j, and high pass, $S\alpha_j$, filters where:

$$\alpha_j = \frac{K_j}{\tau_j S+1} \ . \tag{9}$$

Thus to achieve the overall double integration (S^{-2}) a high pass filter $\alpha_1 S$ is required prior to integration to isolate "dc" components. Next two low pass filters, α_2 and α_4, in series act to achieve the desired double integration. The final refinement is to add two more high pass filters, $\alpha_3 S$ and $\alpha_5 S$, between the low pass filters to achieve the desired band shaping. The resulting filter (See Figure 3.) is fifth order and in the particular case where all τ_j are equal reduces to the general form:

$$\alpha = \frac{K\tau^5 S^3}{(\tau S+1)^5} \ . \tag{10}$$

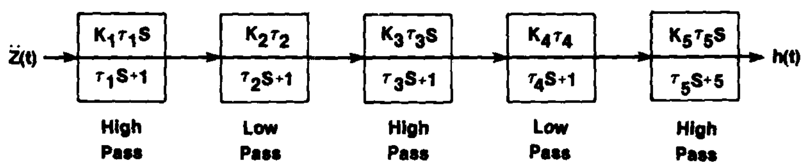

Figure 3. Implementation of Filter for Double Integration.

It is necessary to select τ in such a way as to achieve a frequency response from about 0.1 to 5 Hz for the SES measurements. The current value, which was adjusted from an initial value of 40 seconds to 4 seconds following sea trials, is a compromise between system accuracy and filter settling time.

The circuit as finally implemented is indicated in Figure 4. A special loop (not shown) is also included to compensate the vertical gyro for ship maneuvers.

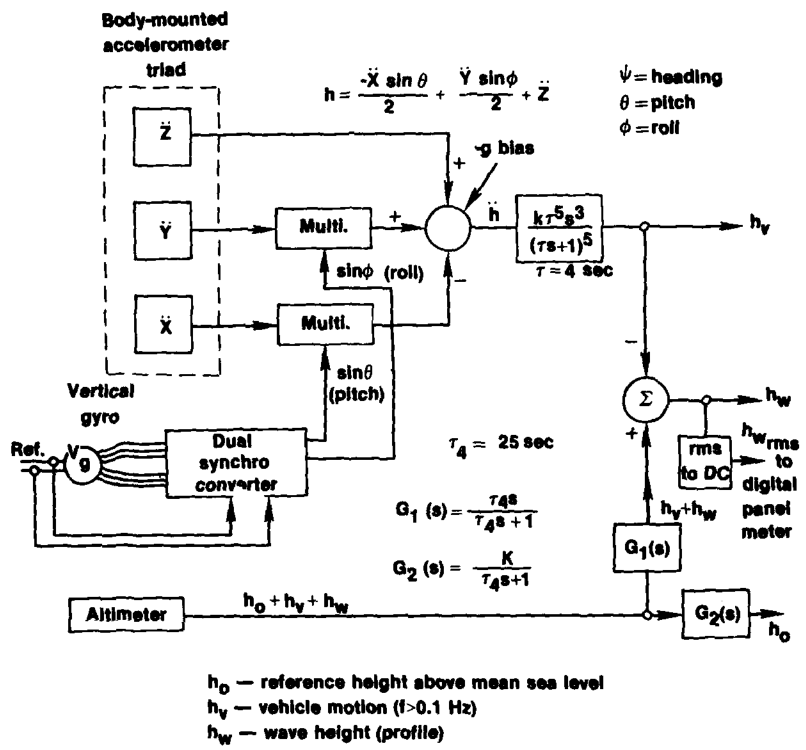

Figure 4. Configuration of the Wave Profiling System (WPS).

Sensors

Altimeters or radars of the acoustical, laser, and microwave type have been considered for the sensor which measures the distance from the sea surface to some reference point on the ship. These radars are special systems which measure distance by employing either pulse or frequency modulation. Since the round trip distance from the sensor to the sea surface and back is so short in this application, pulsed systems[4, 5] fall on the fringe of electronic-counter technology and the frequency modulated (FM) systems are currently much easier to implement.

Two types of radio altimeters were used in the current studies, a "classical altimeter" and a servoed slope altimeter. The basic formulation is the same for both. Consider Figure 5. A triangular

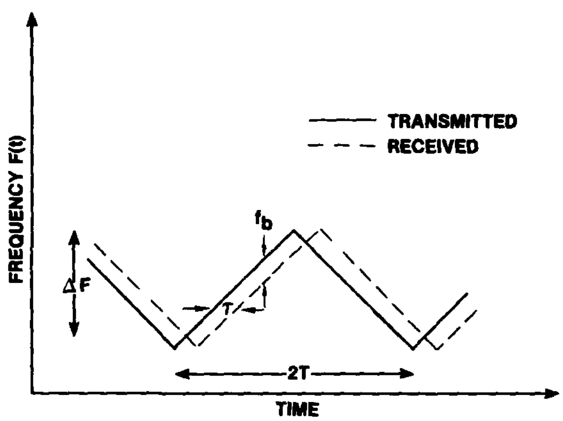

Figure 5. Transmitted and Received Signal Frequencies Versus Time for Periodic Triangular Modulation.

wave is generated by sweeping the frequency up and down in linear sections while holding the transmitted power constant. The transmitted radiation advances to the target surface, is reflected, and returns with a time delay, τ, relative to the initial wave. Due to this modulation scheme there exists a difference between the transmitted frequency $F(t-\tau)$ and the received frequency, $F(t)$:

$$f_b(t) = F(t)-F(t-\tau) \tag{11}$$

Since altitude information is taken from a counter which counts "zero crossings" during the period 2T rather than from a frequency discriminator, a quantization error exists:

$$\frac{\Delta h}{h} \simeq \frac{1}{2Tf_b} . \tag{15}$$

Indeed, one of the commercial grade radio altitmeters used in the development, when tested against laboratory point targets or over calm water,[8] demonstrated a stair-step altitude pattern with step height attributable to the counter implementation of the system. In this particular counter, steps were approximately 1.2 meters in height so the error was significant. The error could have been reduced significantly by reducing the total range of h measured. The lesson here being that "off-the-shelf" equipment which has been designed for high altitude aircraft will have to be optimized for the short range condition. It is also argued that point targets are not representative of the real world and that such quantization steps are filtered out by vertical velocity, complex reflecting surfaces, and intentional artifically induced phase jitter. Seat of the pants judgement tends to reinforce this judgement in part, but large steps surely contribute to a significant measurement error.

The effects of pitch and roll and multiple radar lobes should also be considered. Over a smooth reflector, the only energy returned is that component normal to the reflector surface. Over a rough surface, such as a sea surface, the returned energy will depend on the sea surface and ship orientation. The strongest reflection will be from the normal component. The highest energy will be concentrated in the main lobe. The return will thus be a power spectra consisting of return elements from various radiation lobes and different geometric areas of the wave. The sensor will read some type of power average representative of the composite reflected energy. The lowest frequency component (assuming a positive frequency sweep) will represent the shortest distance to the water surface, but the position of this component will not be well defined due to the finite beam width and to the multiple lobes. Reducing beam width reduces this problem but eventually results in signal drop out since the maximum energy component tends to be specularly reflected rather than diffusely scattered.

A second type of FM altimeter, a servoed slope tracker, implements a spectral leading edge tracking technique in such a way as to provide an extremely narrow fixed bandwidth and a consequent improved signal-to-noise ratio. In this approach (See Figure 7.), the beat difference, f_b, and the range of the frequency sweep, ΔF, are held constant while the half period T is allowed to vary.

Referring to Equation (14), it can be seen that these conditions result in:

$$h = K_1 T \tag{16}$$

where:

$$K_1 = \frac{c}{2} \frac{f_b}{\Delta F} . \tag{17}$$

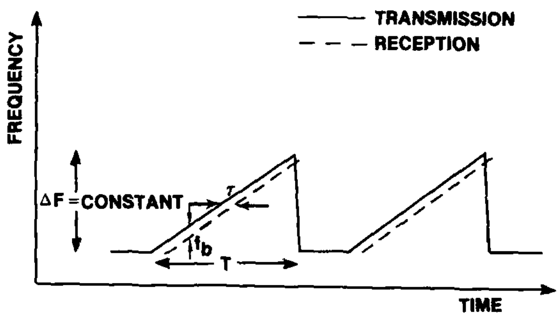

Figure 7. Asymmetrical Modulation Used in Servoed Slope Altimeter.

Instead of using a counter as in the previous case, an error signal is generated (See Figure 8.) by using a tracking frequency discriminator tuned to the desired beat frequency. The error signal in turn controls the modulation rate to maintain a constant value of beat frequency. Since no counting is used, the quantification error is not present. In addition, due to continuous servoing of the slope, the beat frequency remains relatively constant. The receiver can thus have a narrow effective bandwidth.

Over a smooth surface, this system tracks the specular component which again corresponds to the shortest distance. Over rough surfaces the system tracks the shortest distance to the surface; however, in the case of certain sea surfaces, the surface becomes in effect a series of planes or facets. Reflected energy is now available from several angles. The resulting energy spectrum results in a frequency weighted centroid corresponding to a variety of values of h, and the system will not necessarily track the shortest distance. Ship pitch and roll only serves to compound this problem.

Rao and Meads[8] have studied the classical and servoed altimeter. They find that for large beamwidths and over level terrain, the servoed system will demonstrate superior performance; however, the difference in performance decreases over a sea surface as indicated in Figure 9. The indicated relationship is based on the empirically estimated value for the radar cross section, σ_o, of the sea surface. This expression for the cross section applies only as long as the sea surface appears fine grained or "rough" with respect to back scattering of energy.

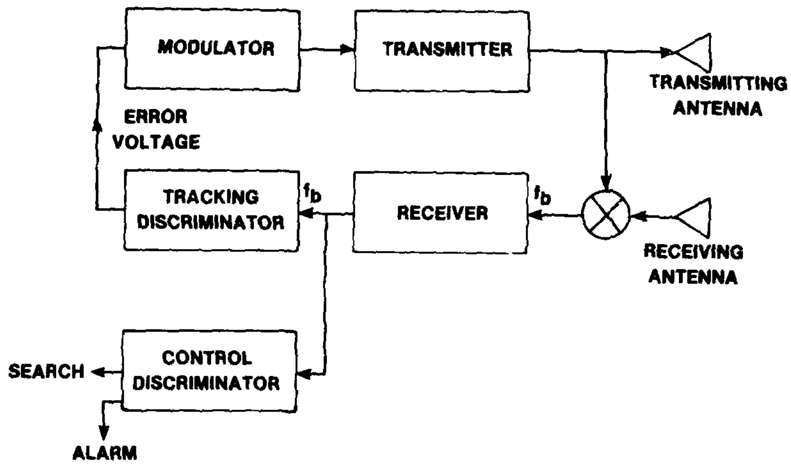

Figure 8. Servoed Slope FM Altimeter.

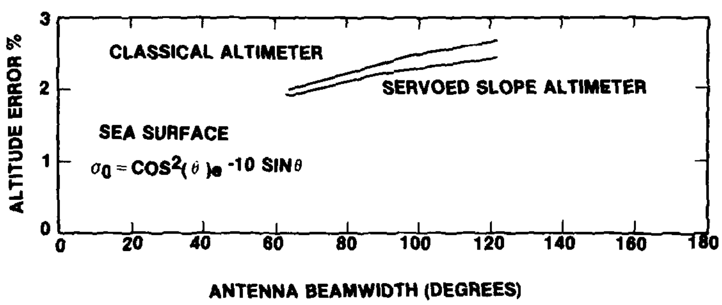

Figure 9. Altitude Error Versus Antenna Beam Width for Classical and Servoed Altimeters.

Thus there is not a great deal of difference between the ultimate performance of the two systems. The difference decreases as the beamwidth is decreased and both become more subject to scintillation and glint problems in this condition. The servoed types seems to be much less susceptible to mutual interference.

Some consideration[8, 9] has been given to applying a laser radar for the sensor. This effort used a 0.9 micron galluim arsenide laser with limited success. The laser approach eliminates the side-lobe problem and presents a well defined beam; however, the crux of the problem remains the nature of the water surface. Calm water is a specular reflector with approximately 2 percent reflectance at normal incidence. Rough water as in the case of radar presents a rough multi-faceted surface. Provided the beam has a "footprint" which is large compared to facet size, the reflection will be diffuse. As the footprint is decreased, glint will again become a problem.

PERFORMANCE

Limited resources led to development of the system as two separate modules: the inertial package and the altimeter package. The inertial package has proved to be the easier of the two developments and work still remains to be done on the altimeter portion. In the process of developing ship speed sensors[10] and special ship radars PMS 304 developed experience with several types of sensors: acoustical, infrared, and radar. In an effort to minimize cost, available equipment was used wherever possible; however, it will probably be necessary to develop special equipment for the ranging application.

Examples of both a classical altimeter and a servoed altimeter, have been tested aboard the 100-ton SES test crafts. The systems were used to develop a real time profile of the encountered waves just forward of the bow and on the craft's centerline. In order to evaluate system performance, the altimeter data corrected for ship and sensor motion was compared to wave height data from a Datawell Waverider Buoy. Data was gathered by making a near constant speed straightline pass in close proximity to the buoy. Data was sampled for about 500 seconds corresponding to 5,000 data points for the Waverider, 16,000 data points for the WPS (Wave Profiling System, the combined inertial package and servoed altimeter), and 500 data points for the onboard speed sensor.

The power spectral density (PSD) of the WPS, S(f), was compared to both the Waverider Buoy PSD, $S_W(f)$, and to a Bretschneider PSD, $S_B(f)$, where $S_B(f)$ was developed as follows:

$$S_B(f) = \frac{A}{f^5} \exp\left(\frac{-B}{f^4}\right) \tag{18}$$

where:

$$A = 4B\sigma^2 \tag{19}$$

$$B = \frac{f_W{}^4}{\pi} \tag{20}$$

σ = rms wave height

$$f_W = \left[\int_0^\infty f^2 \, S_W(f)df \Big/ \int_0^\infty S_W(f)df \right]^{1/2} . \tag{21}$$

The WPS spectrum was in turn established by transforming the onboard measured encounter spectrum, $S(f_e)$, to a stationary encounter spectrum. In terms of encounter frequency, f_e, and wave frequency, f, the encounter spectral density is

$$S(f) = \left| 1-4\pi Gf \right| S(f_e) \tag{22}$$

where:

$$G = \frac{V\cos\psi}{g} \tag{23}$$

g = acceleration of gravity

V = ship speed

ψ = angle of wave encounter

and f is the positive real root of the expression

$$G^2(2\pi f)^4-2G(2\pi f)^3+(2\pi f)^2-(2\pi f_e)^2 = 0 . \tag{24}$$

The power spectra density(11) for one of the better agreeing runs is indicated in Figure 10 and a summary of statistics is presented in Table 1. The degree of agreement in the root-mean-square parameters is better than can be justified on a strictly physical basis. The 500 second run and average ship speed of 34 knots corresponded to a sample extending about 2.5 miles on either side of the buoy. The amount of traffic and the relatively shallow bay area in which the tests were conducted would seem to prohibit this degree of uniformity over the entire test area. In addition, the WPS data was found to be slightly non-stationary during the first half of the run.

A more significant difference is apparent in the cumulative probability histograms indicated in Figures 11 and 12. The waverider data follow a Normal Distribution fairly closely, but the WPS data indicate a significantly higher percentage of large wave amplitudes. This might be partly due to a more accurate measurement of wave peaks, but later tests under slightly different sea conditions indicated that a significant amount of drop-outs were occuring in the electronic tracker. This effect was aggrevated by the particular implementation of the tracker. In the case of commercial altimeters, knowledge of tracking loss is very important; hence, an alarm feature is incorporated into most trackers. In this tracker, the alarm feature is implemented in such a way as to place full supply voltage on the altimeter output when track is lost, resulting in a very rapid onset high value of wave height reading. Although relatively infrequent, these drop-outs can result in erroneous wave height readings and more important could lead to major problems if the data were to be used for a fast response control system.

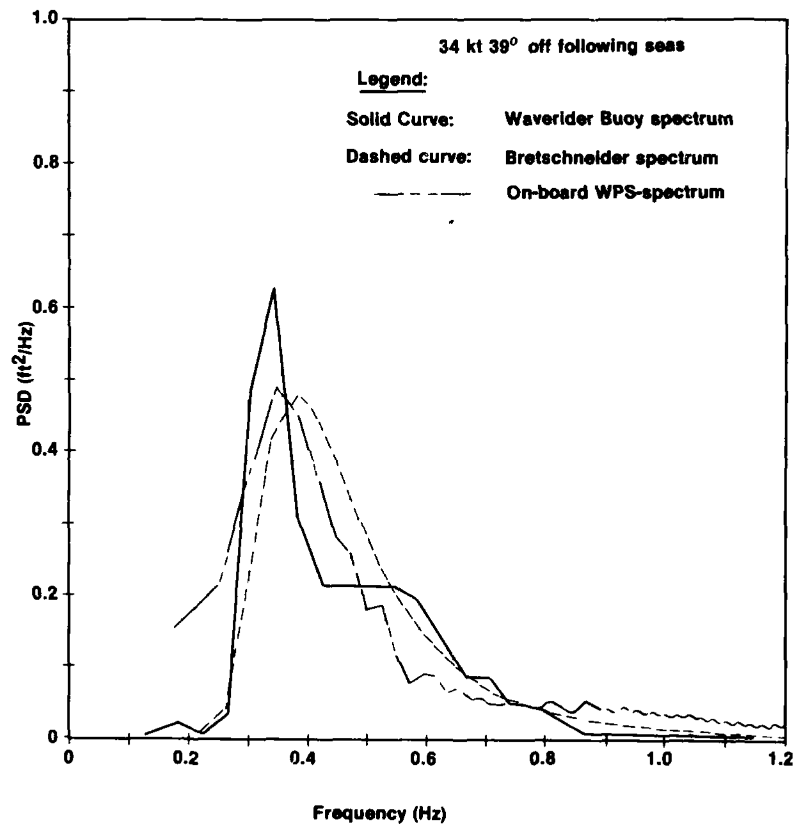

Figure 10. Comparison of the Transformed Encounter Spectrum with the Wave Rider Buoy and Fitted Bretschneider Spectrum.

The obvious fix for this problem is to maintain either a constant velocity or position tracking servo during the relatively short time that the signal is lost. The "alarm" feature has been changed in the present equipment so that the high voltage is no longer fed directly into the output data (tracking loss is monitored by a separate circuit) but the tracking change for constant velocity or position feedback has not been incorporated to date.

Table 1. Comparative Waveheight Statistics for Wave Ride Buoy and Wave Profiling System With Servoed Slope Altimeter

Waveheight Parameter	Value Waverider	Value WPS
Mean	0.121 ft.	-0.015 ft.
Minimum	-1.200 ft.	-1.650 ft.
Maximum	1.480 ft.	2.720 ft.
Standard Deviation	0.387 ft.	0.385 ft.
Significant Wave Height	1.548 ft.	1.540 ft.
Frequency at PSD (max)	0.342 Hz.	0.346 Hz.
Bandwidth at PSD (max)	0.042 Hz.	0.040 Hz.

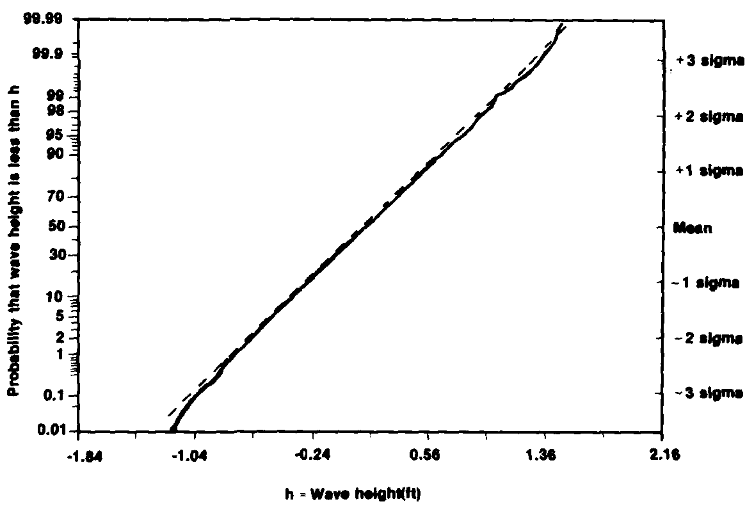

Figure 11. Cumulative Probability with Fitted Normal Density and Wave Rider Buoy Data.

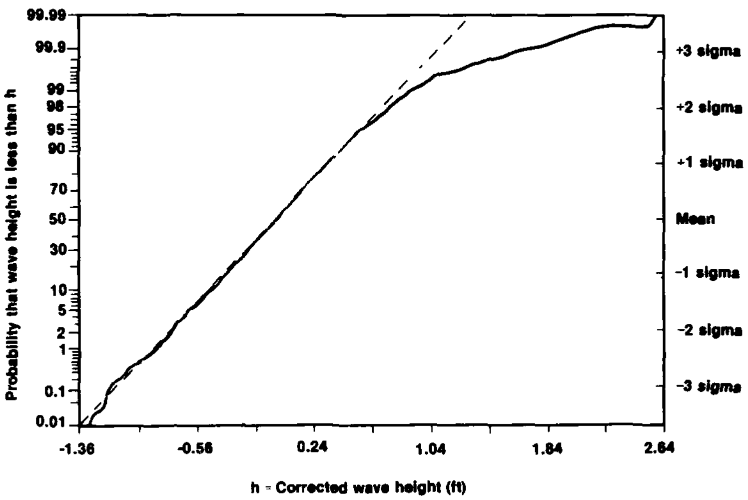

Figure 12. Cumulative Probability with Fitted Normal Density and WPS Data.

CONCLUSION

Systems of this type seem to offer some promise as a means of gathering sea keeping data. The tracking loop provides a positive indication of tracking loss and data can be "sanitized" accordingly. The implementation of the system as part of a control servo still contains some trouble points, the most difficult of which is the inability to provide precise and continuous tracking. In those instances where long term average values are acceptable, drop-outs and pointing accuracies are not as critical and the system should perform satisfactorily.

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HIGH SPEED VELOCITY LOG

A PRACTICAL SOLUTION FOR PRECISE SPEED AND SIDESLIP MEASUREMENT FOR AIR CUSHION VEHICLES

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ABSTRACT

The development of new high speed hull designs has outpaced the requisite development of an accurate water velocity sensor, required for functions such as navigation, fire control and automatic craft control.

In response to this need, the U.S. Navy has undertaken an exploratory development program to determine an applicable High Speed Velocity Log (HSVL) which is self contained, accurate, reliable and which will operate without water contact.

Doppler radar technology was chosen for the prototype HSVL. The Exploratory Development Model HSVL was tested extensively aboard the U.S. Navy Hydrofoil High Point (PCH-1) and the U.S. Navy Amphibious Assault Landing Craft JEFF(B). The results of the testing indicated that a Doppler Radar HSVL is a feasible solution to the problem of Air Cushion Vehicle Speed measurement.

The prototype HSVL now provides total velocity magnitude, sideslip angle, fore-aft velocity and port-starboard velocity inputs for an Integrated Control System (ICS) aboard the JEFF(B). These inputs are essential for speed and stability control functions of the ICS.

The paper will discuss: the installation and testing of the HSVL aboard the JEFF(B); the modifications required to improve operation and performance in the JEFF(B) environment; the interfaces of the HSVL with the JEFF(B) operator and the Integrated Control System (ICS) and; HSVL performance as the primary craft velocity measurement sensor.

INTRODUCTION

The development of new hulls has outpaced the requisite development of shipboard navigation technology in the areas of specialized sensors and systems. The operating environment of these advanced high speed surface ships has imposed constraints on the measurement, processing, transmission and display of navigation parameters and has established unique requirements for velocity sensors. This has necessitated development of a high speed 2-axis velocity log capable of measuring fore-aft or longitudinal and athwartships or transverse velocity components required due to the wide range of operational speeds encountered and to the criticality of sideslip to craft control. The U.S. Navy inventory does not currently contain such a device. In response to this need, an investigation of the feasibility of self-contained 2-axis velocity measurement techniques for high speed surface ships has been undertaken by the Naval Air Development Center (NAVAIRDEVCEN) under the Navy Ship and Submarine Technology Block Program sponsored by the Naval Sea Systems Command. In addition a study of the application of these techn.,.es to the Landing Craft, Air Cushion (LCAC) program has been performed by

NAVAIRDEVCEN under the sponsorship of the LCAC project office of the Naval Sea Systems Command through the David Taylor Naval Ship Research and Development Center.

TECHNICAL APPROACH

NAVAIRDEVCEN issued an RFP to industry soliciting feasibile approaches and techniques for a High Speed Velocity Log with the following characteristics:

- Dual Axis (fore-aft and athwartships velocity)
- 100 knot capability
- Highly accurate
- Self contained
- No water contact
- Negligible contribution to ships electromagnetic or acoustic detection envelopes
- Simple electronic calibration
- Insensitivities to maneuvers and environmental conditions
- Low cost

Since the RFP did not specify a preferred approach to the HSVL requirements, several different technologies were proposed, including acoustic doppler, optical log, doppler laser, correlation radar and doppler radar. An FM-CW doppler radar technique was subsequently selected by NAVAIRDEVCEN for feasibility demonstration and test. Selection of this technique was based primarily on the following:

1. Low technical risk - The technology of doppler radar was highly developed and has been utilized for many years in aircraft for true ground or water speed and could be modified for high speed ship application.

2. Low cost and short lead time - This is based upon utilizing an existing rotary wing aircraft production doppler radar and performing the necessary hardware and antenna modifications and software and interface development to provide a suitable HSVL for shipboard application.

3. No complex processor requirements - The doppler radar front end produces an analog signal proportional to speed along each of the radar beams which is easily implemented to provide real-time velocity outputs.

4. Immunity to spray - The FM-CW method is particularly effective in rejecting spray because of the signal-to-noise ratio (S/N) characteristics of this type of radar. The antenna cross polarization characteristics also gave the sensor additional spray return immunity.

A contract was awarded to Singer Company, Kearfott Division to develop a modified version of their AN/APN-210 helicopter doppler radar for use as a feasibility model HSVL. The modified version was designated by Singer Kearfott as model number SKD-2104.

HSVL HARDWARE DESCRIPTION

The feasibility model HSVL is a Singer-Kearfott SKD 2104 Doppler Radar System which was derived from a rotary wing aircraft doppler radar and was modified to withstand the near water, high spray marine environment (see figure 1). This system operates on the "doppler shift" principle whereby the frequency of a signal shifts in direct proportion to the relative velocity between the signal source and the observer. If either the source or the observer moves toward the other the frequency increases, if moving apart the frequency decreases. This frequency change is the doppler shift. In the present application, a narrow beam radar signal is transmitted from an antenna down toward the water surface; backscattered energy is received by a similar receiving antenna. Employing the

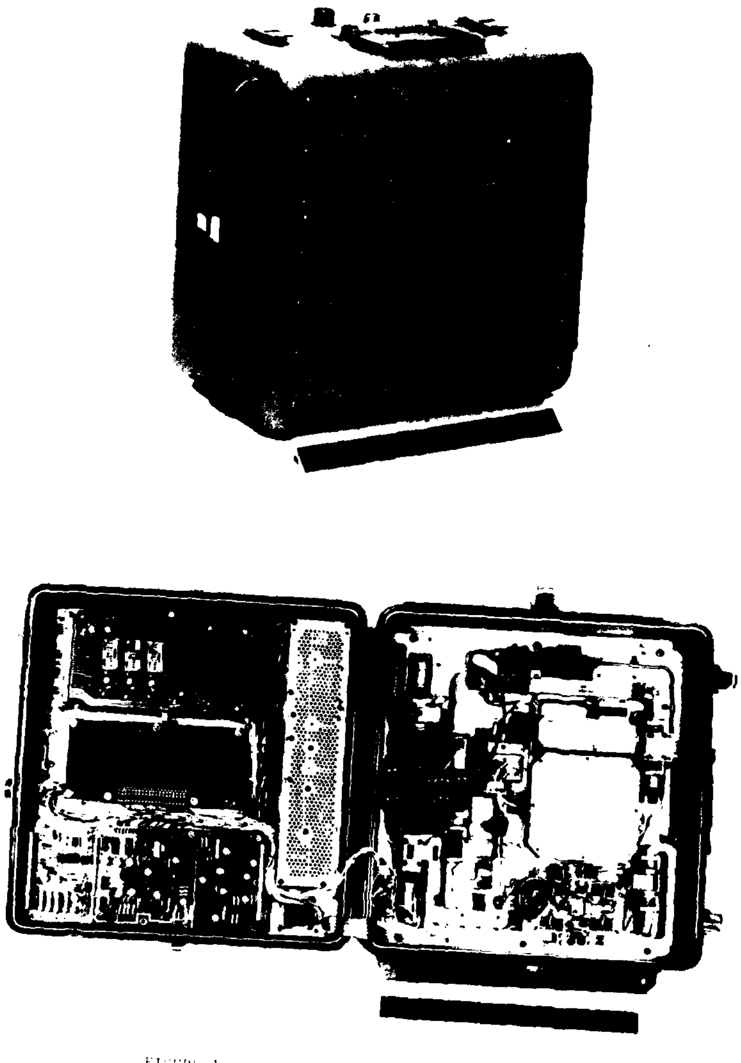


FIGURE 1: HSVL ANTENNA AND ELECTRONICS UNITS

doppler shift principle, the difference in frequency between transmitted and received signals is processed to compute relative velocity between ship and the water surface. Since the velocity measurement is in the direction of the transmitted radar beams, at least three non-coplaner beams are necessary to obtain a total relative velocity vector.

The SKD 2104 is a microwave doppler velocity sensor which operates at 13.3 GHz, FM-CW and uses very low radiated power levels (38.5 microwatts to 38.5 milliwatts). Three narrow beams of microwave energy radiated from an externally mounted transmitting antenna are used in this system (see figure 2). Each beam is directed toward the water surface at a 28-degree angle with respect to the vertical. The returned radar echoes are received by an antenna, amplified and processed in a frequency tracker where a pulse train for each beam is generated. Each of these pulse trains has a repetition rate proportional to the frequency shift. Measurement of these three pulse trains enable determination of ship's fore-aft, athwartships and vertical relative velocity components.

After preliminary testing of the SKD 2104 it was determined that it was impractical to mount the radar in a position where all three beams are clear of structural interference. It was therefore decided to process only the two forward facing beams. Eliminated was the natural pitch compensation provided by the aft facing beam, and as a result it was determined that a signal proportional to craft pitch would have to be provided in order to compensate for variations in measured velocity due to pitch variations.

PHASE I INTERMEDIATE SPEED EVALUATION

Subsequent to delivery of the HSVL hardware, arrangements had been made to install the HSVL in a bow mounted configuration on the Hydrofoil USS HIGH POINT (PCH-1) (figure 3) which was undergoing trials at the Puget Sound Naval Shipyard and on the Hood Canal and Puget Sound in the State of Washington. A bow mounted configuration was chosen in order to minimize the affects on HSVL performance due to motion of the water surface. The test setup, shown in block form in Figure 4 was designed to obtain a calculated output velocity vector simultaneously with range positioning system (Motorola MiniRanger 3) data from which reference velocity could be calculated. The difference in the two velocities would give an indication of the HSVL accuracy potential. In addition, provisions had been made to study the raw doppler returns which were the inputs to the HSVL frequency trackers, the circuitry that detects doppler shift. If the processed output appeared erratic or obviously wrong, spectral analysis of the doppler return could indicate the cause of the problem.

During the early stages of the Phase I evaluation, it became apparent that several modifications would be required to the HSVL to ensure operability in its near water environment that are not required for an aircraft doppler radar. As a result of analysis of the test doppler returns in the frequency domain and a theoretical study of the characteristics of this type of FM-CW Doppler radar, the following modifications were determined to be necessary to achieve operability of an HSVL.

- Cross polarization of the transmit antenna with respect to the receive antenna.
- Installation of polarization grids to increase polarization purity of the antenna.
- Adjustment of the characteristic signal to noise ratio of the HSVL by an analytically derived amount.
- Modification of the doppler return detection circuitry to vary doppler return track acquisition levels as a function doppler shift frequency.

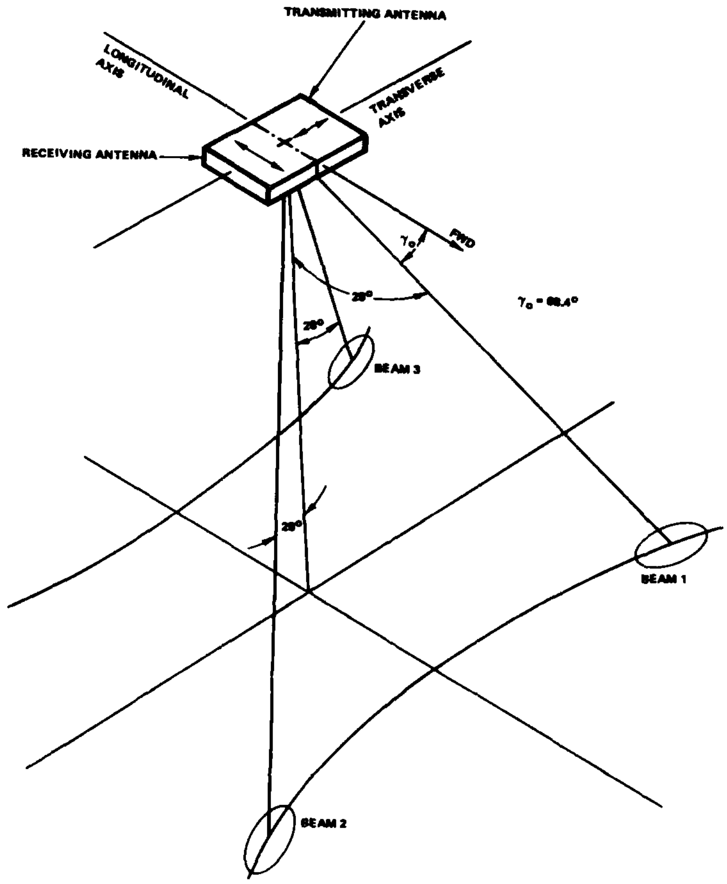
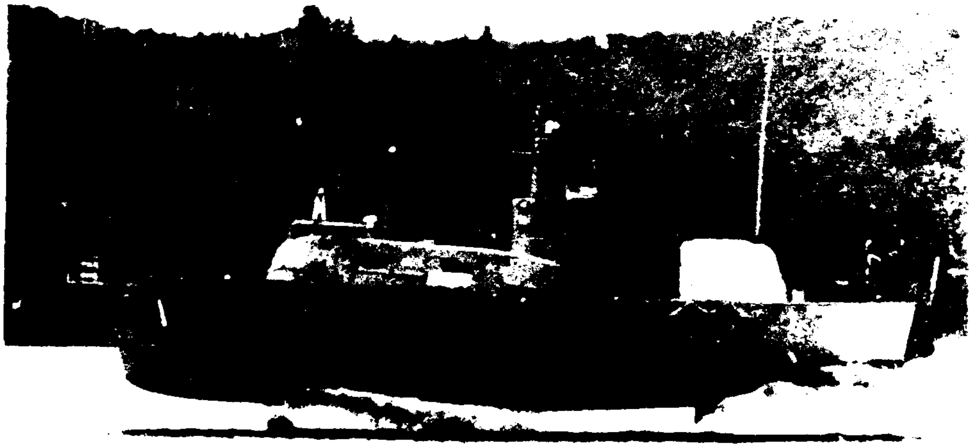
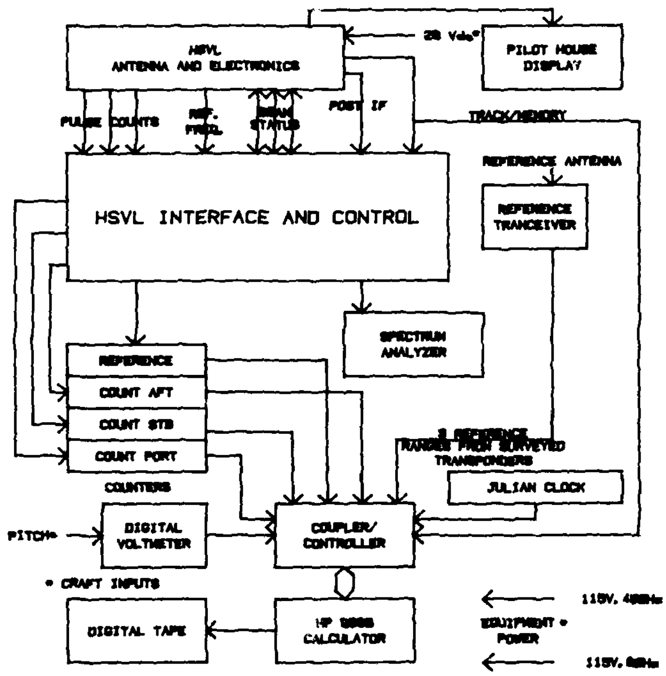


FIGURE 2: HSVL ANTENNA BEAM PATTERN





PHASE I FUNCTIONAL BLOCK DIAGRAM

FIGURE 4

These modifications have the combined effect of rejecting undesired near field unshifted returns from the water surface directly below the HSVL antenna while enhancing the desired doppler shifted backscatter, which is processed to determine vèlocity. A detailed description of the analysis and the enhancement effects of each of these modifications can be found in reference 1.

The first three of these modifications were performed prior to completion of the Phase I testing aboard the High Point. The last modification was performed before Phase II testing aboard the U.S. Navy Amphibious Assault Landing Craft (AALC) JEFF(B).

The results of the tests aboard the High Point verified the effectivenss of the initial three modifications as discussed below.

The processed velocity outputs obtained during the ensuing tests were in reasonable agreement when compared to the range reference system derived velocities over all operable sea conditions encountered. Results of the post test data reduction and analysis indicated that a doppler radar HSVL is a feasible method for providing a highly accurate velocity sensor for high speed hydrofoil craft. The RMS velocity errors of the HSVL obtained during this test (see figure 5) indicated the capability of the hardware to meet the HSVL design accuracy goals. The y axis labels of figure 5 have been removed to declassify the plot. The classified version can be found in reference (2). It should be noted that these results for the HSVL use only the forward two beams, even though information was available from all three beams.

A further result of the Phase I tests and the aforementioned analysis quantified the point at which a doppler radar in a bow-mounted configuration and operating over very smooth water would lose usable return signal. The results indicated that the bow-mounted HSVL would operate effectively when the sea state was greater than GPL 1. Marginal operation would occur for sea states between GPL 1/2 and 1. (See figure 6 for a definition of the GPL Water surface condition scale). This is a classical problem encountered with this type of equipment.

PHASE II HSVL - AMPHIBIOUS ASSAULT LANDING CRAFT OPERABILITY AND ACCURACY TESTS

As a result of the successful conclusion of Phase I, arrangements were made to conduct tests aboard the Amphibious Assault Landing Craft (AALC) LC JEFF (B) one of the two advanced development air cushion vehicles that the Navy is testing (see figure 7).

Due to potential operability problems associated with the anticipated high spray environment aboard the JEFF (B), Phase II was subdivided into two parts. Phase IIA was designed to determine operability in the high spray hovercraft environment and to prepare for Phase IIB performance testing. Phase IIB was established to further determine HSVL accuracy potential and evaluate the addition of a real time velocity processor which provides a digital velocity readout for the helmsman.

Modifications were made to the HSVL to improve its environmental characteristics (e.g., watertight seals, shipboard electrical connectors) and track/acquisition levels and track/memory circuits were adjusted in accordance with the optimum parameters determined from the Phase I data.

The JEFF (B) craft is being operated and maintained by the AALC Experimental Trials Unit (ETU), a field activity of the David W. Taylor Naval Ship Research and Development Center. The AALC ETU is located at the Naval Coastal Systems Center (NCSC) at Panama City, Florida. NAVAIRDEVCEN personnel installed the equipment on the JEFF (B) at the AALC-ETU and the trials were conducted on the NCSC ranges in the St. Andrews Bay and the Gulf of Mexico. During the initial

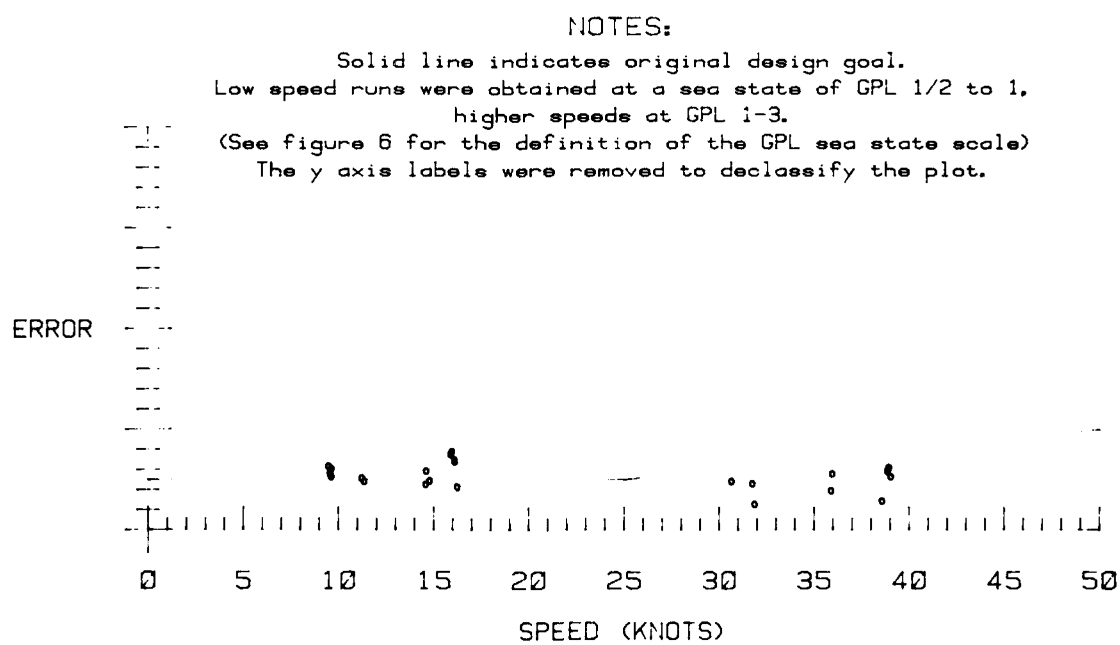


FIGURE 5: PHASE I TEST RESULTS. RMS ERROR FOR 23 RUNS.

TABLE I

GPL "FINE STRUCTURE" WATER SURFACE CONDITION SCALE

(r is the r.m.s. water level deviation of a wave pole with a 3.2-second natural period)

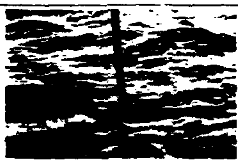
SCALE NUMBER 1/2 Ripples 0-2 in. high r = 0.6 ± 0.2 in. Wind 0-2 knots Calmest water encountered during experiments.		
SCALE NUMBER 1 Ripples 0-2 in. high Waves 1-6 in. high r = 0.8 ± 0.2 in. Wind 0-6 knots More ripples than Scale 1/2, but generally smooth appearance remains.		
SCALE NUMBER 2 Ripples 0.5-6 in. high Waves 4-8 in. high r = 1.0 ± 0.3 in. Wind 0-6 knots Wavelets moving in different directions produce complex surface structure.		
SCALE NUMBER 3 Waves 6-24 in. high r = 1.8 ± 1.0 in. Wind 3-16 knots Waves a few feet in length become more pronounced.		
SCALE NUMBER 4 Waves 24-48 in. high r = 2.4 ± 1.1 in. Wind about 20 knots Whitecaps appear.		

FIGURE 6

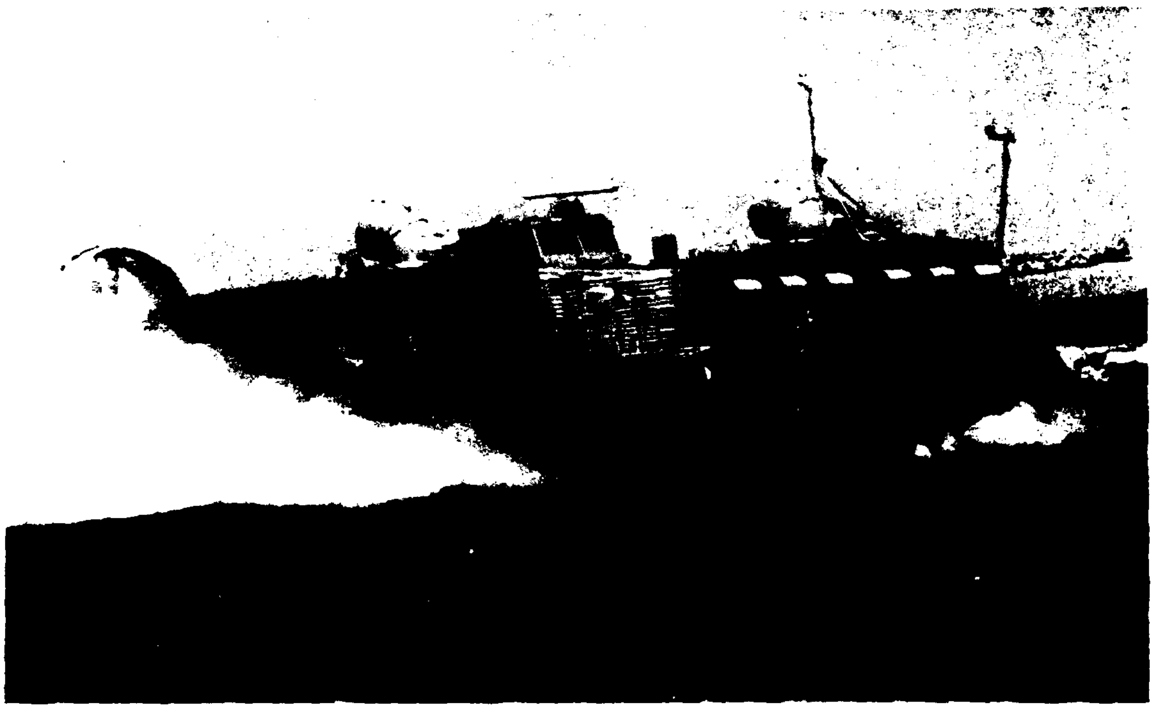


FIGURE 7: AALC JEFF (B) WITH HSVL INSTALLED (ON BOOM OFF THE PORT BOW)

missions, HSVL tracking appeared erratic in marginally calm water conditions. Spectral plots of the doppler return signals were compared to those taken aboard the USS HIGH POINT and it was found that the return signal levels were approximately 6dB less aboard the JEFF (B) than those obtained aboard the USS HIGH POINT. A 6 dB reduction in signal level indicated that only 1/4 of the return energy experienced aboard the USS HIGH POINT was available for processing aboard the JEFF (B). This signal level reduction was attributed to attenuation by spray and water on the antenna surface.

Examination of the signal-to-noise ratio equation characteristic for an FM-CW doppler radar indicated that this could easily be compensated for by doubling the FM modulation index, which can be accomplished by a simple hardware modification (change in a resistor value). As noted in reference (3) spectral analysis of the doppler returns after modification verified that the desired increase in signal-to-noise ratio had been obtained and further testing demonstrated operability in the JEFF (B) craft environment. The HSVL was removed from the LC JEFF (B) for further modification in preparation for Phase IIB, accuracy testing.

A microprocessor controlled velocity output processor (Figure 8) was installed in the HSVL and an output display (Figure 9) for use by the JEFF (B) helmsman was installed. Doppler frequency tracking circuitry was further optimized based on previous test results and the HSVL and test equipment were reinstalled aboard the JEFF (B). A block diagram of the Phase IIB test configuration is shown in figure 10.

Preliminary shipboard analysis of the outputs of the velocity processor, when compared with the velocity reference information provided by the NCSC range tracking system, "AERIS" (Autotape Electronic Range Information System), showed reasonable agreement over a variety of sea states and conditions. A sample comparison of HSVL vs. AERIS is shown in figure 11. Further details of Phase II testing can be obtained in reference 3.

Subsequent to completion of tests, the HSVL remained aboard the JEFF(B) as the primary craft velocity sensor. The HSVL was moved from its mounting boom off the port bow to a location on the starboard bow; closer to the craft. (Figure 12). Because of the new mounting location, additional operability problems were observed due to structural interference because of its proximity to the bow skirt and bow ramp. Modifications to the antenna feed were performed and the HSVL has since performed reliably and accurately.

The HSVL now outputs data at an updated rate of 0.8 seconds to the digital display mounted in view of the JEFF (B) helmsman and relief helmsman. Total velocity and sideslip angle are displayed using seven segment incandescent readouts, along with negative velocity and memory (loss of signal due to smooth water) enunciators. This data is smoothed using a first order digital recursive filter with a lag of approximately five seconds to facilitate reading of the data. When the memory enunciator is illuminated, the data displayed is the last measured velocity prior to loss of signal.

This data is also fed, through a digital to analog converter, to a Light Emitting Diode (LED) vector velocity display, designed by Bell Aerospace Textron (BAT), the contractor for the JEFF (B). This device displays a line whose length is proportional to speed and whose angle off center is proportional to drift angle, allowing the operator to judge craft speed and drift visually.

INTEGRATED CONTROL SYSTEM INTERFACE

Subsequent to Phase II testing, BAT began work on an Integrated Control System (ICS) for the JEFF (B) for craft speed and turning control. The ICS is discussed in detail in another paper presented at this symposium by Mr. A. Coles

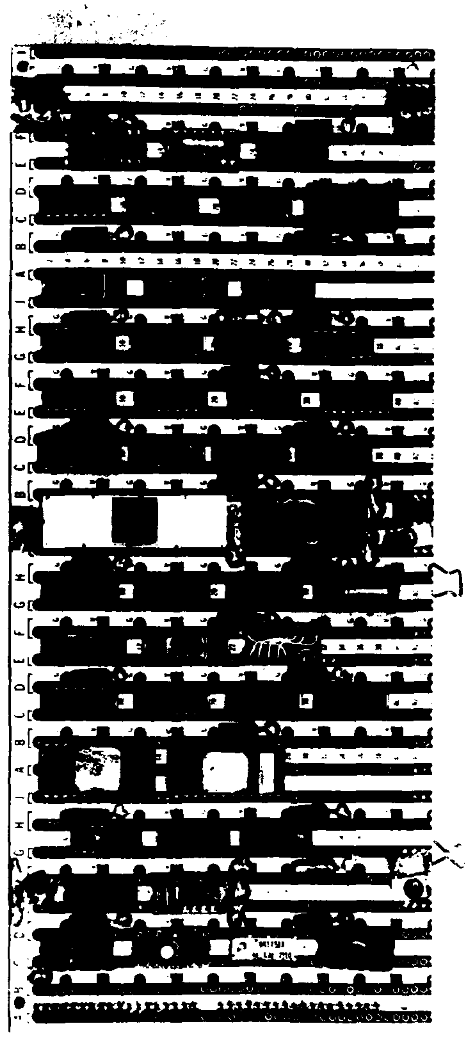


FIGURE 8: HSVL VELOCITY PROCESSOR

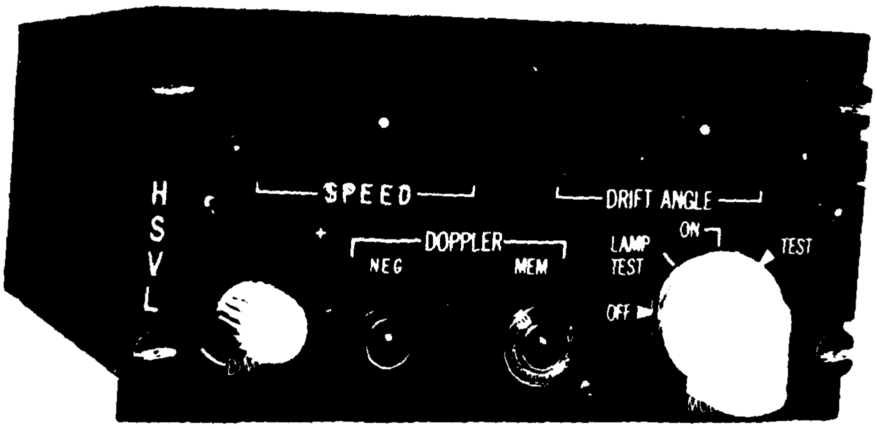
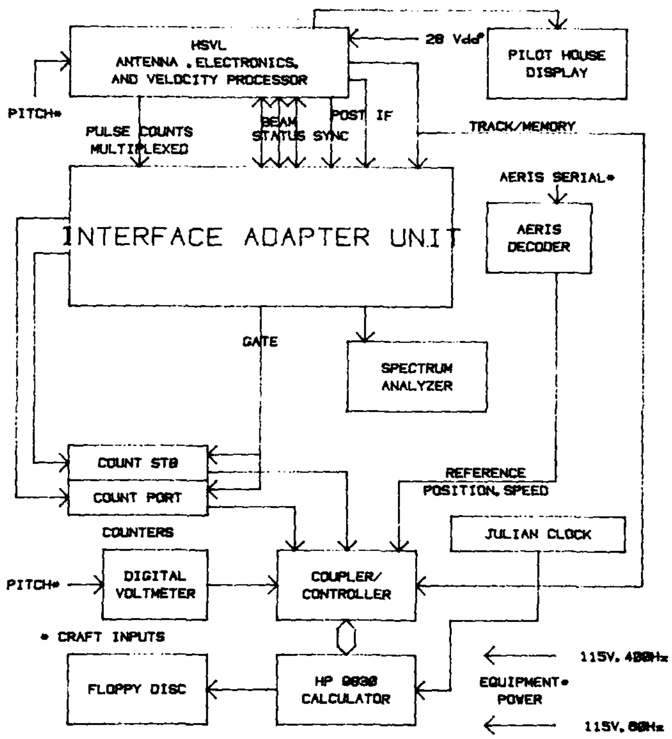


FIGURE 9: HSVL HELMSMAN'S DISPLAY



PHASE IIB FUNCTIONAL BLOCK DIAGRAM

FIGURE 10

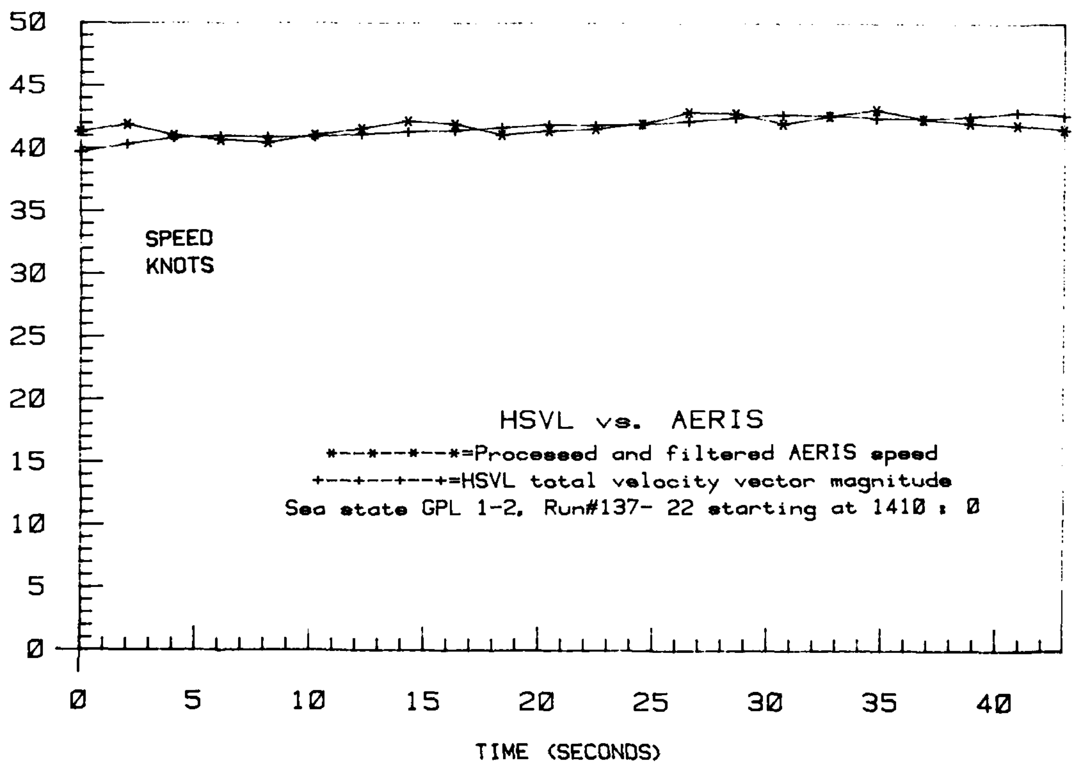


FIGURE 11: PHASE II TEST RESULTS SAMPLE PLOT

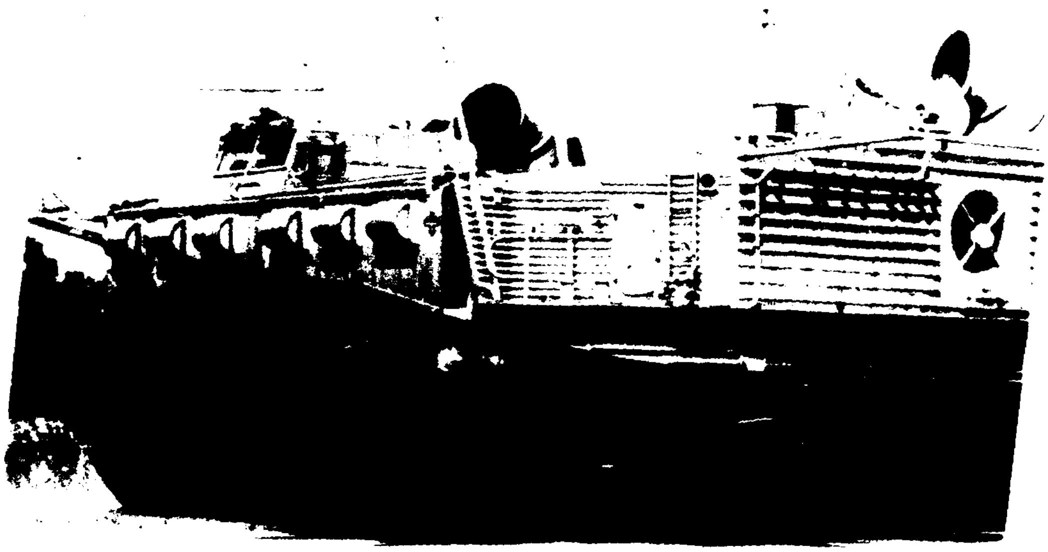


FIGURE 12: HSVL MOUNTED ON THE STARBOARD BOW OF THE JEFF (B)

of BAT and Mr. A. Kidd, AALC-ETU. Because a speed and sideslip input is essential for a control system of this type, NAVAIRDEVCEN was directed by the LCAC project office of NAVSEA to work with BAT to provide HSVL output data and an interface suitable for use with the ICS.

The ICS requires data in the form of the fore-aft and port-starboard components of the velocity vector. In addition, the update rate required is higher than the 0.8 second rate that the HSVL was providing at the time. Software and hardware modifications to the HSVL were performed which enabled output of the fore-aft and port starboard components of velocity at a rate of 0.1 seconds and with no lag or smoothing, while still retaining the total velocity and sideslip angle outputs at their previous rate and smoothing for the Helmsman's displays. The fore-aft and port-starboard velocities were fed to a Digital to Analog converter and then to the ICS. The present HSVL JEFF (B) interface is shown in block form in figure 13.

Preliminary testing of the ICS has indicated the usefulness of these inputs in controlling speed and sideslip of the JEFF (B).

SUMMARY

A microwave doppler radar was selected as the candidate approach to demonstrate the feasibility of providing an accurate two-axis velocity measurement capability for advanced high speed Navy ships such as hydrofoils and air cushion vehicles. This candidate approach was successfully tested aboard the hydrofoil USS HIGH POINT and the air cushion vehicle LC JEFF (B). The results of these tests demonstrated the feasibility of providing accurate dual-axis real time velocity in the operational environment of these high speed surface ships.

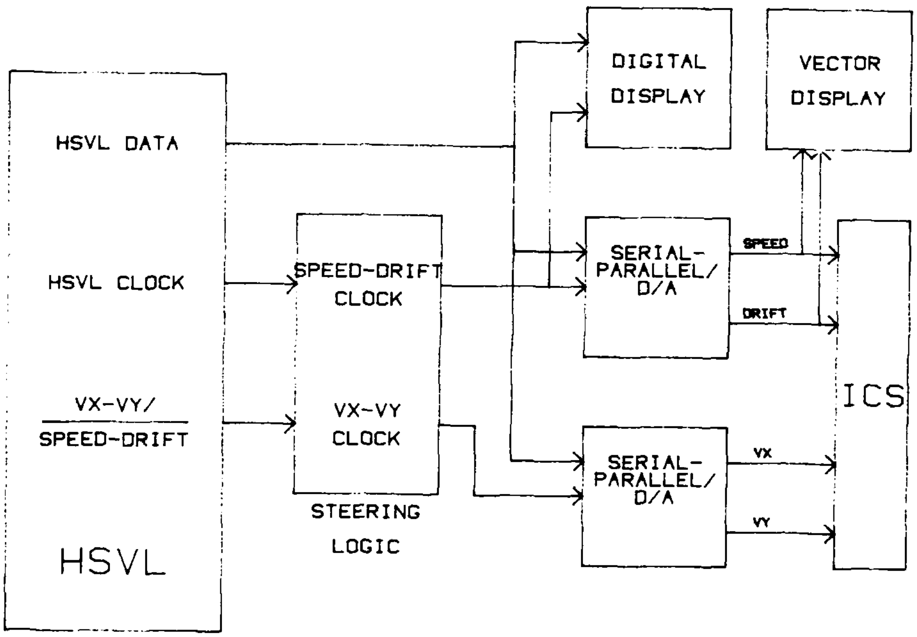
The HSVL is capable of providing speed and sideslip information at the rate and in the format necessary for speed and turning control of a hovercraft such as the JEFF (B) and should be applicable to any such high speed craft.

REFERENCES

(1) NAVAIRDEVCEN Technical Report No. NADC-78228-40, High Speed Velocity Log, Analytical Verification of Performance Over Smooth Water, 1 December 1978 by Neal Barnett.

(2) NAVAIRDEVCEN Phase Report No. NADC-78114-40, (C) High Speed Velocity Log (HSVL), Intermediate Speed Feasibility Demonstration (U), 15 June 1978 by Neal Barnett and Samuel Cheney.

(3) NAVAIRDEVCEN Phase Report No. NADC-80176-40, High Speed Velocity Log (HSVL) Amphibious Assault Landing Craft Operability and Performance Demonstration, 4 August 1980 by Neal Barnett and Samuel Cheney.



HSVL INTERFACE FUNCTIONAL BLOCK DIAGRAM

FIGURE 13

THE MICROPROCESSOR-CONTROLLED PROPULSION
AND MONITORING SYSTEMS OF THE FRIGATE "F122"

by Dr. H. Corleis
AEG-TELEFUNKEN, W.GERMANY

ABSTRACT

The propulsion system of the new German frigate type F 122 is a twin - shaft system with a CODOG propulsion plant which is controlled by automation equipment being based on microprocessors. The automated propulsion system is supervised by an independent monitoring and measuring system also incorporating microprocessors of the same layout .

The system philosophy provides for graded operational hierachies with decentral subsystems which incorporate standardized modules as far as possible and economically feasible.

The hardware of the propulsion control system is composed of two separate control cabinets, one for port and one for starboard control.

The hardware of the monitoring system comprises six independent substations and one main station.

For initiation and indication both independent systems - control and monitoring - are interrelated in the Machinery Control Console (MCC). Besides the central section of the propulsion system the MCC incorporates two further sections, one for the electrical power generation and distribution system at the left wing, and one for damage control, NBC, protection etc. at the right wing. The monitoring system supervises not only the propulsion machinery, but also the electrical equipment and all important ship's auxiliary machinery.

SYSTEM PHILOSOPHY

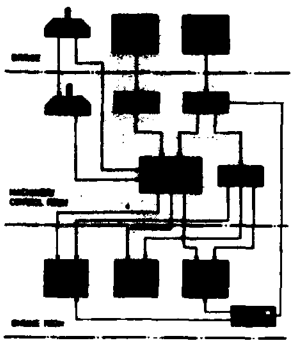


Figure 1. Block Diagram / Propulsion Plant Control F 122

The system philosophy is based on the demand to keep the reliability as high as possible. A high reliability is obtained by means of a clear functional hierarchy, functional independence of subsystems, decentralization, redundancy and self - monitoring .

Four steps of hierarchy, from the bridge down to the LOP's (Local Operation Panels) with increasing independence while going down the steps of hierarchy, ensure the ship's propulsion.

These four steps are :

- Fully automatic control from the bridge (The control lever of the MCC acting as an indicator)
- Fully automatic control from the MCC
- Remote control from the MCC with bypass of the automation system
- Manual control from Local Operation Panels.

The monitoring system comprises six self-supportant substations and a main station for acquisition and annunciation of alarms.

The propulsion machinery automation - one for port and one for starboard - and the six separate substations of the monitoring system are mutually independent as well as functionally and physically decentralized. Failure of one unit does not disturb the functional performance of the remaining units.

Certain vital items of equipment and functions are designed with redundancy, e.g. overspeed protection for gasturbines.

The propulsion control systems and the monitoring systems are provided with electronic self - monitoring. A built-in function simulator permits testing of functional chains by means of test signals.

DESIGN OF THE PROPULSION AND MONITORING SYSTEMS

The propulsion system comprises two propeller shafts, each driven by one gasturbine or one diesel through a gear box via clutches. Power output is performed via controllable pitch propellers.

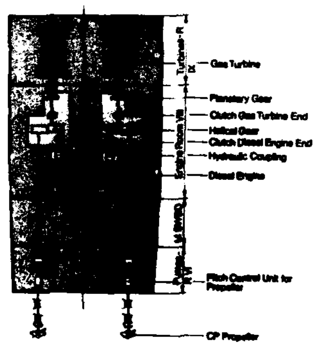


Figure 2. General Arrangement/ Propulsion Plant F122

The man-machine dialog takes place in the Machinery Control Room (MCR) at the MCC and on the bridge at the Bridge Control Console (BCC).

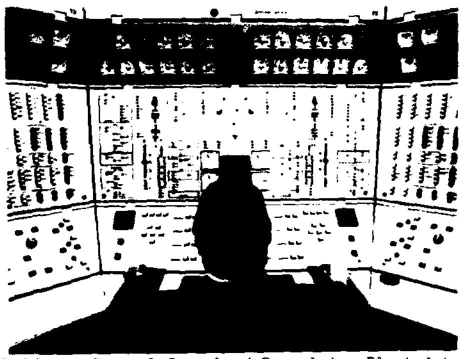


Figure 3. Machinery Control Console / Propulsion Plant Automation F 122

The MCR contains the triple - sectioned MCC - Electric Power, Propulsion, ships service system, each divided into two parts, the actuating zone (desk) and the monitoring zone (mimic diagram). By this means all controls and displays are arranged around the operator .

The Duty Officer's Console, arranged in front of the MCC, allows the duty officer total supervision and command initiation.

The propulsion system and the monitoring system are located in separate control cabinets with the assemblies being functionally grouped in their pertaining housings (19"), this arrangement consists of three cabinets for the propulsion electronics and six for the monitoring system electronics.

The Bridge Control Console is divided into three sections. The central section is the place of the control operator, the left-hand section is the helms-man's position and the right-hand section is the bridge Duty Officer's position. The remote control and indication facilities comprise the two control levers for propulsion, the two mode and operating mode selection panels, ship-related analog instruments and communication facilities.

Local Operating Panels for the propulsion diesel engines, the gasturbines and propeller pitch control are each provided for "on-plant" control as a fourth emergency mode of control.

Functional Description

The following four control modes are possible :
- Fully automatic control from the Bridge
- Fully automatic control from the MCC
- Manual remote control from the MCC
- Manual on-plant control at the LOP's.

Automatic Mode. The automatic control device ensures maximum torque in maneuver mode and maximum power in normal mode, dependent on the speed torque characteristics of the diesel engine and the gasturbine .

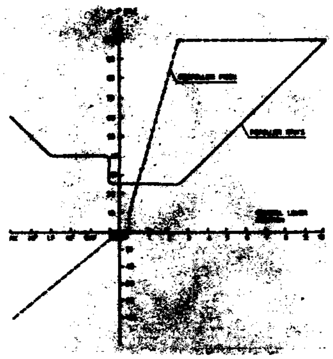


Figure 4. Normal Mode Program/ Propulsion Plant Automation F 122

Remote Control. Dependent on the different characteristics the propulsion machinery can be remotely controlled in accordance with the specified speed charts bypassing the automation units. In this case there are no interlocks between the various controls.

Manual Control. In emergency operation the propulsion machinery, clutches, CP propellers etc. can be manually controlled at the LCP's.

System Layout of Electronics

Hardware. The hardware of the propulsion plant control system comprises only a restricted number of assembly types. The basic component is a CPU card with a microprocessor for management of data transfer routes, I/O bus and memory bus.

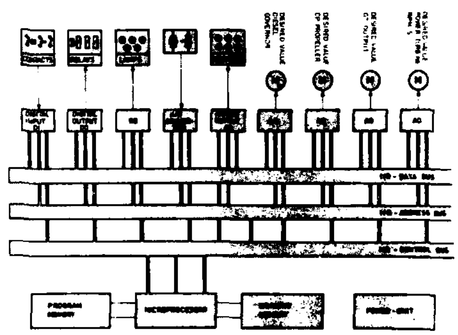


Figure 5. Microprocessor Control Unit / Propulsion Plant Automation F 122

The following standard modules are used : Power unit, CPU cards, memory cards (PROM, RAM), A/D converters, digital input and output units, analog output and parameter input units. Control inputs and displays are effected via panels at the MCC (Machinery Control Console).

A system monitoring unit provides cyclic monitoring of the CPU, a cyclic memory check of the RAM's and PROM's, monitoring of the A/D converter with test signals and monitoring of the system voltage.

In the event of power failure availability of all data is ensured for a further period of 20 hours.

Software. The software comprises the system software, which controls the programs for internal computer operations and data exchange with the periphery and the user program for the process-specific functions. The system software comprises program management, interrupt management, restart, I/O systems, operator terminal and software clock. The user software is provided for the specific tasks to be fulfilled, whereby the modular design and control of processing via lists offers increased flexibility.

Simulation Facility. Each Propulsion automation unit has a built - in simulation panel for the checkout of automatic functional chains, thus permitting the checkout of control loops of the automatic unit by means of test signals.

DATA ACQUISITION AND MONITORING SYSTEM

The propulsion plant is monitored by the data acquisition and monitoring system, which serves for automated centralized monitoring of all ship's engineering systems, i.e. propulsion machinery, auxiliary machinery.

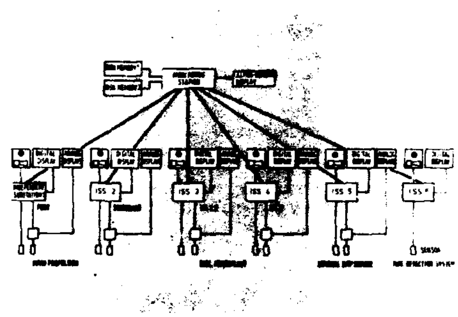


Figure 6. Data Logging/ Propulsion Plant Automation F 122

Substations

The system is shown in Figure 6 and comprises a main station and six sub - stations, as follows :

- SST 1 : Propulsion plant port
- SST 2 : Propulsion plant stbd.
- SST 3 : Generator set VII
- SST 4 : Generator set X
- SST 5 : Ship service systems
- SST 6 : Fire alarm systems.

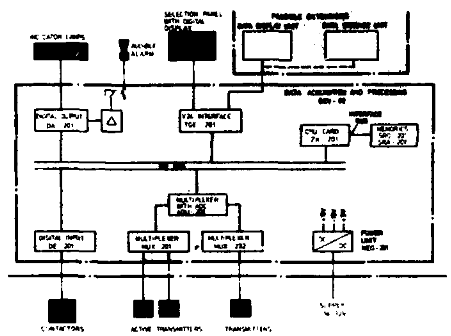


Figure 7 . Block Diagram Substation / Propulsion Plant Automation F122

The substations are designed for completely autonomous operation and provide data acquisition, processing as well as audible and visual alarm annunciation in the mimic diagrams and indicator panels. The substations also control the display selection units for digital display of actual operating values and the applicable upper and lower limits for the individual monitored points .

Main Station

In addition, the data are transmitted from the substations to the main station. The main station processes the data and also provides communication between the substations and the data peripheral units.

The peripheral units comprise a data display unit, two data loggers (disc memory) and a terminal for a printer. These peripheral units permit storage of a certain data quantity and malfunction messages from the substations for approx. 1 hour.

The data display unit permits display of monitored points and sections, i.e. either actual operating values or stored values from the data loggers.

Thus the operator at the MCC is provided with a general survey of plant conditions and can take further measures without having to leave his position.

The Main station and the substations of the data acquisition and monitoring unit are of similar design as a microprocessor - controlled system and composed of the same standardized assemblies as the propulsion automation system.

TRAINING CENTER

The main taks of a training facility with such a complexity is the on - the - job - training of the ship's crews.

Advantages of using a training facility are :

- Each member of the ship's crew gets used to operate that part of the ship's system he will be responsible for when on duty
- Special actions necessary under severe conditions can be learned without running the risk of damaging equipment
- Team training of a ship's crew as under realistic conditions aboard the ship can be performed
- The facility can be used to train maintenance staff for failure analysis and repair.

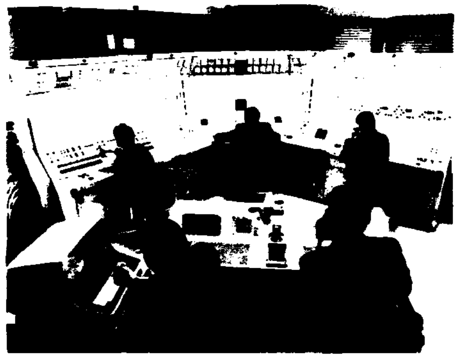


Figure 8 . German Frigate F 122 / MCR, Training Center

Scope of Equipment

For the above described training purposes the following equipment is installed in the training center :

One complete Machinery Control Room (MCR) in the same configuration as installed aboard the ship (see Figure 8).

The MCR includes the following equipment :

- Machinery Control Console, being divided into three sections :
  on the left the control and monitoring section of the electrical plant of the ship
  in the center part the control and monitoring section for the propulsion plant
  on the right the control and monitoring section of the ship service systems, damage control, leakage control, fire fighting and NBC protection.
- The Duty Officer Console is equivalent to the console installed in the center of the room, allowing supervision of operation.
- The electronic equipment being part of the data acquisition and monitoring system is installed at the left side of the MCR.
- The electronic equipment for the Propulsion Automation System is installed at the right side of the MCR.

In addition to the above described simulation equipment that is completely equivalent to the on-board equipment within the MCR
- a bridge control console and
- local control panels for both gasturbines of the propulsion plant

are installed for training purposes, especially with regard to the different operating modes of the system.

For realistic operation of the equipment installed in the MCR the functions of
- Propulsion Plant
- Electrical Plant
- Ship's Service System

are simulated by an especially developed simulation system.

Simulation System. This system comprises :
- the complete Propulsion Plant i.e. simulation of a twin shaft propulsion with controllable pitch propellers, hydraulic and self-shifting clutches, gasturbines and diesel engines
- the complete Power Supply System including 4 diesel - generator sets, 2 Main -

Switchboards, the power distribution system and consumers
- the Ship Service System.

The above mentioned simulation devices are controlled by a master computer, which interconnects the simulation devices and the equipment in the MCR.

The complete Simulation System consists of five electronic racks, each having the dimensions : 80 x 80 x 200 cm (width x depth x height).

To allow training under disturbed conditions a teacher's desk is installed in the rear of the MCR (behind the Duty Officer Console).

From this teacher's desk most of the functions of the simulation system can be influenced in such a way that a disturbance or a failure in different parts of the system are simulated at the MCC.

Finally a printer connected to the master computer has to be mentioned. This printer allows the print - out of the actual status of the Ship's systems as well as the continuous print - out of the operations initiated by the trainees during a test course.

FIRST EXPERIENCES

After having finished the construction of the first hardware set of the propulsion electronics and monitoring equipment, a hot-check of the systems was carried out, including all consoles, bridge equipment, local control consoles etc. with simulation of the peripheral elements and conditions.

The tested system was given on board, and after integration test together with the real periphery first sea trials were carried out.

Only 5 hours of the 24 hours planned were necessary to become sure that the system could be handed over to the main contractor.

CONCLUSION

First experience gained with preproduction types of the equipment described above has shown that software and hardware are functioning properly and at the same time producing the required results.

This revealed that the approach to the solution was a successful step in the right direction, i.e. to achieve a control and monitoring system of the desired functional performance and reliability by employing latest technology and data processing procedures.

CONTROL AND SURVEILLANCE OF SHIP SYSTEMS BY MEANS OF VDU'S AND DIGITAL PROGRAMMABLE COMPONENTS

by J. Brink CDR(E) R.Nl.N
and J.F.D. Kuypers LtCDR(E) R.Nl.N.

ABSTRACT

Progress in technological development and the tendency to reduce ship complements have given occasion to critically reconsider the excisting machinery control rooms in order to optimize the man-machine interface and to achieve a reduction of the personnel on duty, resulting in more personnel available for fault analysis, corrective and preventive maintenance.
The capabilities and development potential of a digital computer system with VDU's were reasons to consider the implementation of such a system for operation and surveillance of platform installations (machinery, power) on board future ships of the Royal Netherlands Navy.
In the paper the philosophy and the design, the advantages and disadvantages of control and surveillance systems by means of VDU's and digital computer systems is discussed.

INTRODUCTION

Apart from the explosive development of electronics, which has created ever increasing opportunities (technical and financial), automation of technological systems has been the result of the stringent requirements to reduce the continuously rising through life costs, in the personnel field as well as in the material field.
To reduce the costs of manpower continually less personnel is available in the Royal Netherlands Navy.
The reduction of the number of engineering personnel (mechanical and electrical) on board ships of the R.Nl.N., amongst others the result of design, is illustrated in table 1.

Table 1. Number of engineers employed

	Commissioned (1st of type)	Number of engineers per 1000 HP total installed power	Number of engineers per 1000 tons standard displacement
Destroyers "Friesland" Class	1956	1.35	31.6
Frigates "Van Speyk" Class	1967	1.33	17.3
Frigates "Tromp" Class	1975	0.85	11.4
Frigates "Kortenaer" Class	1978	0.60	9.7
Frigates "M"-Class	-	± 0.60	± 7.8

Furthermore a wish to improve the working conditions of the personnel on duty exists. Automation of the operating and instrumentation systems makes control and surveillance from an airconditioned and soundresistant controlroom possible.

In the material field operating costs can be reduced by introduction of more sophisticated systems. Maximisation of the reliability of a machinery system by technical means rapidly becomes non-cost-effective due to high investment costs. The alternative is to reduce human error as much as possible.
Research shows that the possible error frequency rate considerably increases from 1 : 1000 for routine work (simple tasks) to 1 : 4 for complex non-routine tasks in emergency situations and that the chance of human error by operating a variety of machinery systems is relatively higher than the chance of mechanical breakdown (1).
A correct application of the technology to the human capabilities is of greatest importance.

At the design stage of the Guided Missiles frigates of the Tromp-class in the second half of the sixties, the decision was made to have unmanned engine rooms and a machinery control room (MCR) from which control and surveillance of the propulsion, electrical power supply and NBCD is possible. The design and technology of the Dutch standard frigates of the "Kortenaer"-class was based on the GM-frigates.

Progress in technological development, the tendency to reduce ship complements and the wish for higher reliability by eliminating human errors, have given occasion to critically reconsider the excisting MCR's on board of Dutch warships in order to optimize the man-machine relation and to achieve a reduction of the personnel on duty, resulting in more personnel available for fault analysis, corrective and preventive maintenance.

GUIDED MISSILE - AND S - CLASS FRIGATES

The automation of the Guided Missile- and S-class frigates was based upon the following philosophy, established in the second half of the sixties (2):

- to create an engineering centre where all information concerning the state of mechanical and electrical engineering plants, as well as NBCD, will be available;
- to permit watch to be kept on unattended machinery spaces by providing suitable means of operation and surveillance of main and auxilliary machinery and associated systems;
- to reduce the number of watchkeeping personnel to a minimum by presenting data concerning the aforesaid machinery and systems in such a way that one person can view and operate as many instruments as possible.

The above mentioned considerations led to automation of machinery installations and centralization of control and surveillance in a machinery control room.
Of the platform systems, among other things, the propulsion and electrical power generation is automated:

- The remote control system of the propulsion installations, built by Fokker Aircraft Industries, contains start/stop functions of the gasturbine, the fuel programmes, the engine selection system, the propellor pitch control and the shaft brake control. Remote operation, either from bridge, operations room or machinery control room is possible by means of the push button telegraph system.
- The automatic dieselgenerator start/stop system for the electric power generation, manufactured by Van Rietschoten and Houwens, controls the dieselgenerator start/stop procedures, dieselgenerator surveillance, automatic synchronisation, load sharing between running engines and reconfiguration in case of electric disturbances and diesel drop out.

The following decisions were made for the MCR (Figure 1):

- The control panel is divided in three main sections (electrical power generation, propulsion and auxiliaries, NBCD). In front of every part of this panel a watchkeeper can be seated.
- The panel design is such that the maximum amount of information is presented. It was necessary to provide the watchkeeper with only fault indicators. This resulted in avoidance of space-consuming dial type instruments, where possible, and application of alarm/warning annunciators and indicator lamps, grouped together in coloured frames adhering to the all dark principle.
- To avoid time-consuming manual recording, machinery data-logging equipment was installed (Decca ISIS 300 System).
- An additional alarm/warning system supplied by an alternate power supply of 24V DC is installed in case of failure of the 440V powersupply.

Figure 1. MCR of GM-frigates

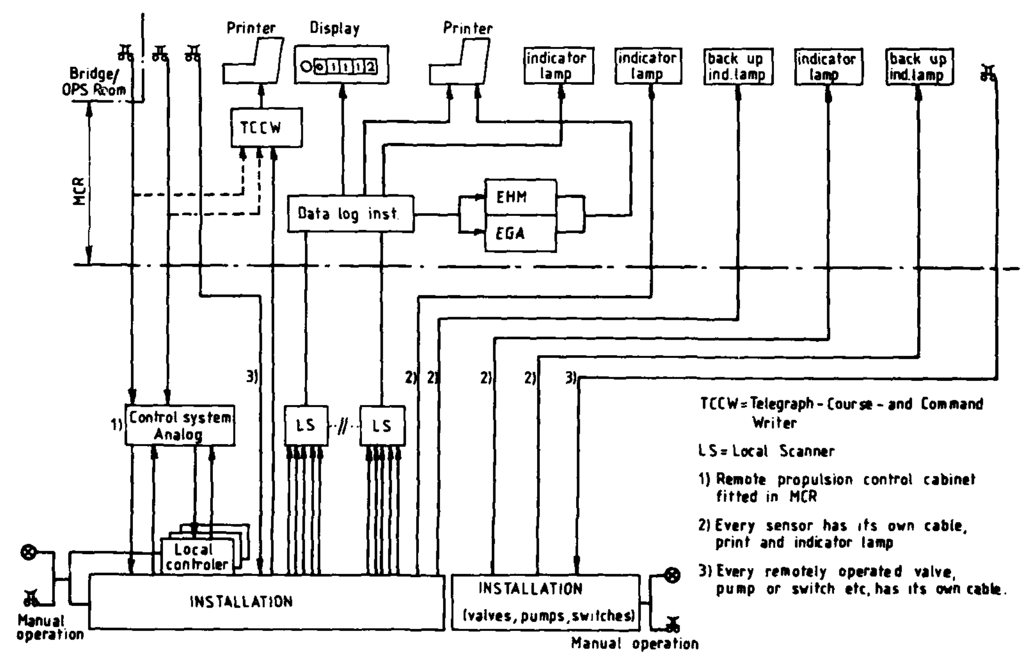
The watchkeepers in the MCR at sea consists of a chief of the watch (chief petty officer), a corporal (electric or mechanic), 3 mechanics and 1 electrical mechanic.

RESTRICTIONS AND DRAWBACKS OF TECHNOLOGY USED ON BOARD GM- AND S-CLASS FRIGATES

The applied technology on board GM- and S-class frigates corresponds to the state of the art at the end of the sixties and is characterized by:

- modular construction
- hardwire logic
- discrete logic components
- different control system suppliers

Figure 2 shows the principle of control and surveillance of the platform installations.



PRINCIPLE OF OPERATION, CONTROL AND SURVEILLANCE OF PLATFORM INSTALLATIONS OF GM- AND S-FRIGATES.

Figure 2

Although the afore mentioned systems certainly have worked satisfactorily and have proven to be extremely reliable, some disadvantages exist and are as follows:

- Modifications and developments of the system are very difficult to implement;
- The cable density, in the vicinity of the MCR, is very high since each input and output, requires its own cable;
- Due to the variety of manufacturers, interfaceproblems had to be overcome.
- Despite the many indicators often the information in the MCR is still limited for fault analysis;
- Alarmregistration is restricted by the maximum number of available channels;
- Due to the large dimensions of the control panels it is very difficult for one operator to survey all information in the MCR.
  Furthermore information interpretation is very often not easy because of changing operation conditions and relatively high incidence of irrelevant information, due to domino effect of faults.
- The modular lay-out and the number of manufacturers means a great variety of modules and consequently many spares to be kept in store.
- Condition monitoring of the machinery installations is becoming more and more attractive as a maintenance philosophy.
  Since computing facilities are not present, condition monitoring is not possible with the existing systems. On board of the S-class frigates a performance monitoring system, only for the gasturbines, is installed retrospectively.

MODERN DATA PRESENTATION

To meet the tendency of complement reduction on board ships it is necessary to implement a system of control and surveillance enabling reduction of personnel on duty in order to have more men available for fault analysis and maintenance. Furthermore it is desirable to reduce the maintenance load and costs. A reduced manning standard is possible when the criterion on which maintenance is carried out, is based on the condition of the installation rather than on a periodic basis.

A smaller watchkeeping party in the MCR is only justified when the operator can survey the information from all machinery systems and can cope with this information, in a stress situation.
The use of visual display units (VDU's) operated by a digital computer makes it possible to present information selectively.
In the process industry and large electrical power stations, it can be noted that conventional survey- and control panels, as an interface between operator and process are more and more superseded by digital programmable systems with VDU's.

The capabilities of computers gave rise to the Royal Netherlands Navy consideration of application of such a system for control and surveillance of the platform installations of the submarine now under construction.

CAPABILITIES OF DIGITAL PROGRAMMABLE SYSTEMS ON BOARD SHIPS

The application of computers for surveillance and control is characterized by:

- A greater flexibility with regard to design and modifications.
  Within certain contraints an existing system can be adjusted by software modifications without hardware consequences.

- Selective data presentation:
  Only the data necessary for the operator at that moment can be presented automatically or on request.
- Mathematical calculations of process data are possible.
  I.e. for condition monitoring.
- Greater information density.
  Compared with the conventional control- and surveillance panel the application of VDU's provides considerably more information on a panel of smaller dimensions.
- Reduced cable density to the MCR:
  Cables are expensive, space consuming, vulnerable and sensitive to interference. Multiplexing of signals gives a considerable reduction in cable density.
- A smaller variety of modules:
  By integration of systems and application of standardized components the variety will be minimal.
- Built-in automatic and periodic function tests:
  Internal failures will be traced and localized automatically and thus minimize the time for fault-finding.
- Automatic reconfiguration of data handling in case of component failures:
  When a computer is inoperative its task can be taken over by a second computer.
- A digital programmable system with VDU's is not tailored to a special type of ship or process but can be used for all types of ships.

DISADVANTAGES

Besides the advantages of digital programmable computer-systems the disadvantages should be mentioned:

- Complexity:
  The methodology of solving problems is shifted from hardware to software. New methods of documentation with the help of flow-diagrams and programme-listing have to be applied.
  In the design stage the working of installations has to be discribed by the designer in great detail, covering all possible conditions to enable the programmer, who in general has no knowledge about such installations, to write the software. A good software documentation is absolutely essential to enable software maintenance, i.e. debugging and modifications.
- Loss of overall view.
  Without special measures, such as the application of fixed mimics, or running light panels the total view is lost by using VDU's.
- Introduction of a new system:
  A complete new system will be introduced. Investigations have revealed that this causes resistance especially with older people, operators as well as managers.
- Training:
  Training facilities and the training of personnel have to be adjusted to the introduction of this new system.
- Experience:
  The introduction of computers can cause problems in the preliminary stage.
- Costs:
  The development of software by high-skilled technicians consumes a great deal of the initial costs.

DESIGN PHILOSOPHY OF THE DIGITAL COMPUTER OPERATED CONTROL AND SURVEILLANCE SYSTEM

For redundancy reasons three independent parts of the control and surveillance system can be distinguished (Figure 3):

Integrated control & Surveillance system

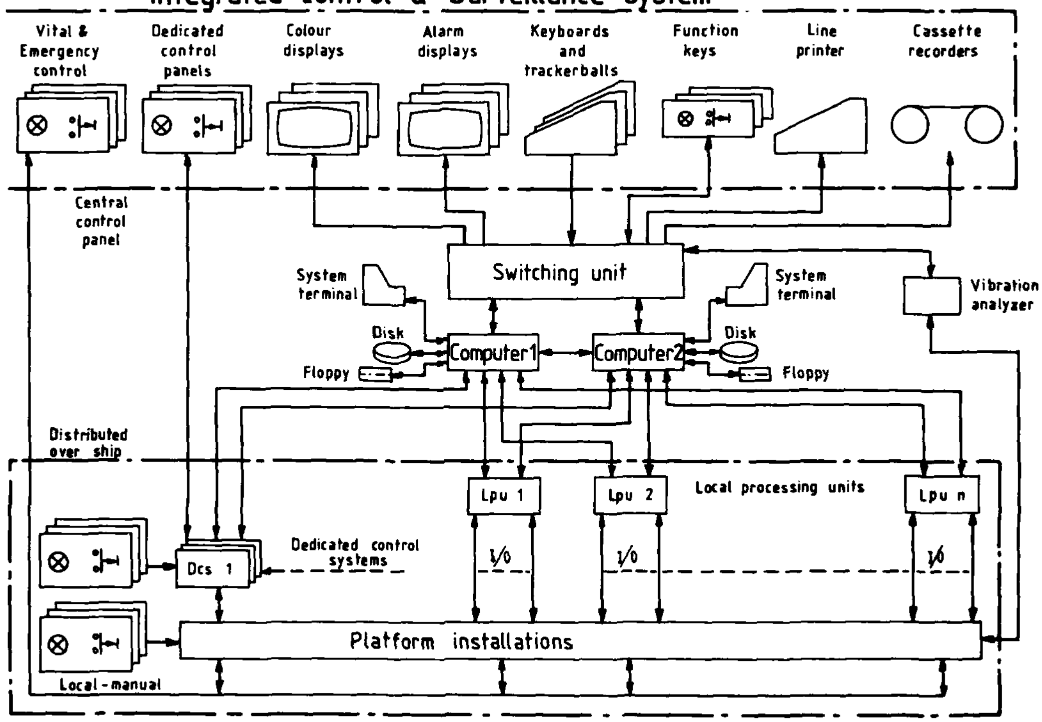


Figure 3

- the dataprocessing system (DPS)
- the dedicated control systems (DCS's)
- the vital and emergency controls

Together they form the "integrated control- and surveillance system".

The dataprocessing system

Vital parts of the DPS are redundant. To prevent a breakdown of the total system in case of a central computer failure two central computers working parallel share the data handling task. Normally each central computer works at less than 50% of its capacity and is completely informed about the status and contents of the database of the other one.
If one of both central computers would fail the other will take over automatically without unacceptable time delay.
Each local processing unit (LPU) has two connections, one to each of the central computers. Disturbance of one of these connections does not effect the proper working of the DPS. Via the "intercomputer link" and the remaining connection the required contact between the central computers and the LPU can be maintained.
Under normal conditions surveillance and control can be shared between the operator positions in the MCR. In case of a defect of one of the VDU's, reallocation to an operable VDU station is possible. Furthermore, although less easy, all operator tasks can be performed without the use of a colour VDU.
The LPU's support the central computers. All platform installations are connected with the DPS via LPU's. The LPU's are closely situated to concentrations of signals. The function of a LPU is:

- to generate output signals in accordance with operator commands to the machinery installation;
- to test input signals on alarm condition;
- to send periodically status messages to the central computer, containing information about measured parameters and their eventual alarm condition.

The function of the central computers is:

- to collect status messages from the LPU's to build up a database of the condition at the input and output of the LPU's.
- to present information to the operator via VDU's, i.e. alarms, installation mimics, trendgraphs, background information;
- to transfer operator commands to the LPU's;
- to store data on magnetic casette tape recorders;
- to monitor the condition of machinery installations.

Each computer is provided with an external memory, i.e. a fixed head disk and a floppy disk. Programmes and data are stored on the disk memory. The floppy disk is used for loading programmes and vibration monitoring.

The plasmapanel is used to present α-numeric information.
Occuring alarms will be presented automatically with mention of ordernumber, time, actual value/position, limits, mimic codenumber. A flashing asterix in the alarm message and an accoustic warning must attract the attention of the operator. The operator can acknowledge the alarm by means of the keyboard and the flashing asterix will disappear.
Alarms will be displayed in time order.

The latest alarmmessage is always written above the former alarmmessage. If the screen would become too full, the oldest alarm will scroll off the screen. However, the oldest no accepted alarm will still be displayed. The operator can scroll back the "disappeared" alarms. Longlasting alarmmessages can be wiped off the screen by the operator, but will be stored and be able to be recalled. The number of deleted alarms will be displayed continuously. Background information will be displayed on request.
This information contains sensor position, limits, type, actual value.
The priority of this kind of information is low and occuring alarms will always be presented. The bottom lines of the plasmapanel have been reserved to display operators commands.

Mimics of machinery installations (or part there of) have to be selected by the operator and will be displayed on the colour VDU on request. The mimics show in red colour all alarms that exist in the corresponding installation. The status of the installation e.g. valve open/closed: pump on/off; flow/no flow, can be concluded from the colour. Furthermore dynamic values are presented, e.g. pressures, temperatures.

The colour VDU can be used to give commands to the installation, by positioning a cursor on a valve, pump, etc., in the presented mimic by means of the trackerball and pushing the special open/start or closed/stop keys on the keyboard. Apart from mimics, trends of selected parameters showing their history in an adjustable time will be displayed on request.
Also the vibration spectrum as result of vibration analysis by the FFT-analyser of measured equipment can be displayed on the colour VDU's.

The keyboard is not standard typewritter keyboard because of the long response times, but has been especially developed in close cooperation with IZF, the institute for human factor engineering. The keyboard contains a number of coded keys, grouped in accordance with their functions.

The dedicated control systems.

The dedicated control system of a machinery installation or parts there of must be considered to belong to that installation. The control systems must be located closely to the installations, they control and work completely independent of the DPS. The philosophy is, that such a decentralized system can still fulfill its task in case of disturbance of the central computers and in the other way round malfunction of a constrol system does not influence other systems.

The dedicated control systems can be operated from the MCR or locally on the control system cabinet.

In case of failure of a dedicated control system, manual operation via DPS or via vital/emergency controls is possible.

The vital and emergency controls.

Failure of the DPS or a dedicated control system of e.g. propulsion installation, is not allowed to cause a situation where remote control of important installations is not possible. Provisions to enable operations of these systems is therefore required, whilst also the most essential information must be presented.
For these reasons hardwired controls and indicators, which are completely independent of the DPS and dedicated control systems, are present in the MCR for these important systems.

As can be seen in figure 3 all installations can be operated locally by hand.

Sensors

As a consequence of the division of the integrated control and surveillance system in three independent parts, sensors for information presentation via DPS or for vital/emergency control should as a minimum have galvanically separated outputs, whilst the dedicated control systems must have their own sensors, to enable the operator to survey the dedicated control system via the DPS and to take action if required.

Also for those installations which require independent safeguarding, e.g. dieselengines against low lub oil pressure, independent separate sensors are needed to ensure that the installation is protected against serious damage, even under the extreme condition that the operator or related dedicated control system does not take proper action if necessary.

THE INTEGRATED CONTROL AND SURVEILLANCE PANEL IN THE MCR.

In the MCR the number of operator positions is determined by the tasks to be performed at "action stations". On surface ships, the tasks under these conditions will be split in propulsion control, electric power generation and distribution control, NBCD control and overall supervision by the MEO, whose position is behind the three operators.
Each position is provided with a colour VDU, plasmapanel, keyboard and trackerball.
Furthermore each operator position has function keys and emergency/vital controls dedicated to one of the above mentioned functions.
To enable a reduced watchkeeping party under normal conditions control and surveillance of the machinery installations can be devided over the minimum number of operators by means of the "installations allocation panel". Depending on workload of the operator or operational circumstances it will be possible to allocate all installations to only one operator.

All keys and indicators are grouped in such a way, that those frequently used, can be easily reached or viewed by the operator. Keyboard and trackerball are fitted in the horizontal plane and other frequently used keys in the lower vertical plane adjacent to both VDU's.
In the upper part of the panel emergency control buttons and indicators are fitted. Sitting in his chair the operator is able to reach the emergency keys.

CONCLUSIONS

Among others automation is a result of the stringent requirement to reduce the continuously rising costs of exploitation, in particular those of manpower.
The limited crew and the wish to improve working condition of the personnel on duty, resulted in unmanned engine rooms and centralization of control and surveillance in a machinery control room.
Progress in technological development and the tendency to reduce ship complements have given occasion to critically reconsider the existing MCR's in order to optimize the man-machine relation and to achieve a reduction of the personnel on duty, resulting in more manpower available for fault finding, corrective and preventive maintenance.
The last few years, in industry, the interface between automated installation and the operator in attendance, has been liable to considerable changes. The "visual display units" (VDU's) which are very flexible for data presentation, are predestined to replace the conventional operator panels as primary interface.

Although such a system does not offer only advantages, the capabilities and development potential of a computer system with VDU's were reasons to consider the implementation of such a system for operation, surveillance and control of platform installations on board future ships of the Royal Netherlands Navy. In 1978 it was decided to introduce digital computers and VDU's on board the "Walrus" class submarines under construction now. The set-up of the design is such that this system is also suitable for all types of ships. The design offers sufficient redundancy to enable remote control, even if the dataprocessing system is completely out of order. As a consequence more sensors are required.
On-line condition monitoring is feasable using only a few additional sensors The number of VDU stations in the MCR is based upon action stations. In normal conditions it will be possible to allocate all operator functions to only one VDU station.

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NEW FACTORS AFFECTING U.S. NAVY MACHINERY CONTROL SYSTEM DESIGN

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ABSTRACT

Machinery centralized control systems were introduced into the U.S. Navy primarily to reduce operational manning. Although numeric manning is still a concern, other factors, such as operator and maintainer skill levels, training requirements, hardware reliability and vulnerability, and energy conservation considerations have affected control system design. This paper examines some of those factors and their impact on current and projected control system designs.

INTRODUCTION

The U.S. Navy introduced its first electronic machinery centralized control systems in the mid 1960's, when essentially commercial "automation" packages were installed on the LKA 113 and AFS 4 Classes, and the AE 32 series of the AE 26 Class.

The Navy expected the centralized control systems to permit a reduction in shipboard manning, similar to the reductions that commercial ships had obtained.

Those expectations were not realized. A Navy study(1), conducted in 1979, concluded that Navy ships with centralized control employed as many, or, in one case, even more watchstanders than equivalent ships without centralized control. The results of the study can be explained by a number of factors, including fleet conservatism, use of watchstanding as a training mechanism, and assignment of watchstanders to stand guard over marginal equipment.

In any case, it has become clear to Navy centralized control advocates that we cannot rely upon manning reduction as the sole, or even as the primary, argument in favor of centralized control. That change is just one of a number of new factors affecting U.S. Navy machinery control system design.

HABITABILITY

Although we are no longer actively advocating centralized control as a means for reducing numbers of watchstanders, we do feel that control systems have definite benefits in regards to watchstations. Watchstanders assigned to machinery spaces are exposed to the heat, humidity, dirt and noise associated with those spaces. They therefore suffer the efficiency losses, morale problems, and physical effects that are a byproduct of that environment. Watchstanders assigned to air conditioned, noise-insulated control stations do not experience those problems. It is therefore desirable to move as many watchstations as possible from the machinery spaces to the control stations.

The Navy's commitment to movement of watchstations has fluctuated over the past few years. An executive order[2], signed by President Ford in 1974, required U.S. Government activities to meet the same standards that were imposed on commercial activities by the Occupational Safety and Health Act of 1970. Included in those standards was an 8-hour noise exposure limit of 90 dBA, which effectively restricted machinery space watchstanding. The Executive Order was subsequently canceled by President Carter[3], and not replaced by any firm guidance. However, the Naval Sea Systems Command has decided to limit watchstander noise exposure to 85 dBA[4]. This limit can be satisfied even in quite noisy spaces by the use of one or two levels of ear protection. Since use of ear protection devices generally makes routine communication difficult, it is desirable to move at least normal control operations to a separate control station; this has been done in most of our recent non-nuclear surface ships.

The movement of routine controls to a remote location has a secondary effect. Since machinery space personnel are no longer forced to stay in a single location to handle normal orders, they are free to move throughout the ship, checking, aligning, and securing equipment and systems as necessary. This freedom means that a watchstander will not always be instantly available to respond to casualties detected by control system instrumentation. It is therefore necessary to provide, as practical, remote instrumentation to detect and initiate handling of credible machinery space casualties. The definitions of "practical" instrumentation and "credible" casualties must, legitimately, be allowed to vary among ship types and missions. However, it is suggested that valve, pump, purifier and engine controls necessary to stop movement of flammable fluids within a space represent an absolute minimum; fire danger is universal.

VULNERABILITY

Whether provided to reduce manning or to increase watchstander comfort, remote centralized controls pose a vulnerability problem: damage to the space in which the centralized controls are located can put the controls out of commission, without physically effecting the machinery being controlled. Such a casualty should not disable a ship.

In recognition of the centralized control vulnerability problem, the Navy has always insisted that remote controls be provided in addition to, rather than instead of, "conventional" local controls. Thus, upon failure of the remote controls, operations can be moved to the local controls.

The problem with reversion to local controls is that local controls, in general, are not as "smart" as remote controls; they offer few of the interlocks, permissives, automatic sequences and other features that are frequently provided as part of centralized control systems. The local operations, therefore, require more operator care than centralized operations, and thus should be supervised by well-trained personnel. This requirement occurs at just the time when those same well-trained personnel may be needed to help put the centralized system back into working order.

It is obviously desirable to have control systems "fail soft," in the sense that failure of sections, particularly physically colocated sections, of a control system should result in loss of as few control system functions as possible. The "fail soft" goal can be attained by scattering control system processing circuitry into various locations in the ship. In particular, it is reasonable to locate the control and monitoring circuitry associated with an individual piece or a logical group of machinery, close to that machinery; this minimizes the probability that damage related to the machinery causes damage to the machinery's control circuitry. Thus, there is a strong and logical survivability argument for the use of distributed control systems. The Navy has

not gone to distributed control yet, but we anticipate that it will in the near future.

With application of distributed control comes the application of *digital* multiplexing, and the question of which multiplex standard to use. This question should not be resolved within the machinery control community alone. There are many other potential multiplex users on board ship, and there is no reason for them to use systems incompatible with the one used for machinery control. The Navy is currently in the final steps of testing and evaluating a multiplex system designed to serve the inter-space data transmission needs of nearly all shipboard equipments. This system, called the Shipboard Data Multiplexing System, or SDMS, can accept and output data in many different forms, including contact closure, d.c. analog, synchro, and a.c. analog. However, its preferred digital interface is the 960 kbit/sec. bit-serial standard that has been codified as NATO STANAG 4156. We are currently planning to use the 4156 interface for inter-space communication in distributed machinery control systems. However, we would like the control system to be easily adapted to other multiplexing arrangements.

MAINTAINABILITY

The introduction of microprocessors into machinery control systems has created a major problem for the Navy. On our older control systems, each circuit board had only a few functions on it: four or five AND gates, or two or three flip-flops. A moderately trained technician equipped with a few schematics and a multimeter could troubleshoot the system.

Newer, processor-based control systems are not as simple. The processor, which performs hundreds of functions within the same space that previously accommodated only one of two functions, changes states with a dizzying speed and, to a maintainer, total unpredictability. Schematics are useless tools unless they are supplemented by program listings and descriptions. Multiplexers, demultiplexers and data busses pass and process bits and bytes at rates that make multimeters as useful for troubleshooting as sledgehammers. The maintainer who can make sense of that confusion has to be an intelligent, highly trained technician. He represents a considerable investment on the part of the Navy, which usually provides a substantial portion of his technical training.

That maintainer is valuable to the Navy; his skills are applicable not only to control systems, but also to weapons, navigation, and communication equipment. He is also valuable to industry, which needs his skills to service or design processor-controlled items ranging from toys to photocopiers to cars to factories. Therefore, the Navy, once it has trained a control system technician, is forced into stiff competition with industry to retain his or her services.

This competition is combined with another problem: the supply of manpower, both skilled and unskilled, will continue to decrease for at least the next decade.

When the Navy began installing centralized control systems, the "post World War II baby boom" babies were approaching young adulthood. The men in that group, who were subject to the U.S.'s military draft, guaranteed the armed forces a generous supply of manpower. Today, the draft is gone, and the last member of the baby boom has passed the minimum enlistment age. Since anybody who will run a Navy ship 18 years from now is alive today, we can look at the U.S.'s aging

population, and at its expanding economy, and predict with certainty that the manpower problems we have today are going to be worse tomorrow. In fact, a U.S. Government demographer has predicted that youth unemployment in the U.S. will drop to zero by 1985[5]. Therefore, the best the Navy can hope for is a miminal share of the coming shortage.

During that shortage, it will be imperative that the Navy make the best use of the manpower it can get. In particular, we will be unable to afford the luxury of keeping people in shore-based technical training schools for months on end; we will need them on ships. We will therefore be forced to severely reduce the skill levels needed to troubleshoot control systems.

What skill levels can we expect to get? For the short term, we can use the people who operate and maintain the machinery the control system is monitoring and controlling: the boiler technicians, electrician's mates, machinist's mates, and gas turbine technicians. In the long term, we can expect that other technical areas will experience the same shortage of trained personnel that we are now seeing in electronics. The Navy may then be forced to withdraw its remaining skilled personnel, of all types, to intermediate and depot maintenance activities, and to man its ships with a legion of operators. Those operators will be able to handle routine maintenance and troubleshooting tasks, but not much more. Those operators may represent our ultimate skill level.

Fortunately, careful application of even today's hardware and software technology can bring control system troubleshooting tasks within the capabilities of the "ultimate operators." We can build systems that automatically detect and indicate failure of individual printed circuit boards, power supplies, and other components. Such built-in self-test features will be a requirement for future control systems; we can afford no less.

TRAINING CAPABILITY

Of course, even "ultimate operators" will require some operator training. In order to get the best use of the operators, it is desirable that as much of that training as possible be done on the job. Use of distributed control offers the possibility of using the centralized controls as a training aid.

During times when control and monitoring operations can reasonably and safely be moved to local stations, the Main Control Console can be disconnected from the normal data bus and connected to a processor-driven simulation of the "missing" portions of the control system, associated machinery and ship systems. Operators can then be trained in routine as well as casualty control procedures with minimal disruption of normal operations and without endangering any machinery.

Switching between normal and training operations can be done without physically moving any cables; the switching can be done by logic within the multiplexing system itself. SDMS includes such a switching feature.

RELIABILITY

Some of the early Navy electronic control systems had so many problems that when an alarm sounded, the first thing the crew suspected was control system trouble. We've come a long way since those days. Much of the reliability improvement is the result of the replacement of individual transistors, resistors, and diodes with small, medium, and now large-scale integrated circuits.

There is every reason to expect that advances in electronic, and particularly semiconductor, technology will continue to offer us ways to improve control system reliability.

However, a monitoring function is only as good as the sensors that feed information to it, and a control function is only as good as the actuators that carry out its commands. Unfortunately, the technology of those sensors and actuators has not advanced as rapidly as integrated circuit technology; sensors and actuators are rapidly becoming prominent as the weakest link in the centralized control system chain. We have taken two steps to minimize the impact of those weak links.

The first and most obvious step was to minimize the number of sensors and actuators we use. This involved reducing, where possible, the number of functions that are remotely monitored or controlled.

The second step was to minimize the impact of sensor and actuator failures. This step took the form of a reduction in the number of interlocks and permissives designed into control systems, so that individual sensor failures do not disable or disrupt machinery or system operations.

Those two steps are, at best, short term solutions. Future control system operators are likely to depend on automatic, sensor-requiring control system features in the same way that most American drivers now depend on automatic transmissions: they can't do without them. We will therefore have to find some reliable, acceptable way of accommodating those operators.

The preference, of course, is for improved sensors and actuators. Some of the technology for those improvements may be here today, just waiting to be adopted. For example, we might substitute Hall effect limit switches for mechanical ones, or replace noisy analog potentiometers with noise-free optical encoders. Other improvements will be the products of new technology; the increasing use of electronics in cars may well result in such changes.

If we can't get suitably reliable sensors and actuators, it appears that a "middle ground" between fully manual and fully automatic systems should be used. Such a system might incorporate a cueing arrangement which, upon detecting a potentially dangerous condition, stops, informs the operator of the condition, and then gives the operator the choice of overriding the permissive which prevents the condition, or aborting the operation. The control system would then act in accordance with the operator's choice.

One solution to the sensor and actuator problem that we are not seriously considering is the use of redundant elements. The use of, for example, dual redundant elements would approximately double the maintenance involved with those elements. Redundancy is generally unacceptable because of the space, weight, and cost effects of the increased hardware, and the manning effects of the increased maintenance.

ENERGY EFFICIENCY

Energy usage has always been a concern in ship design, if for no other reason than the relationship between fuel rate and ship range. However, the increase in fuel prices that followed the 1973 OPEC oil embargo has forced the Navy to put a new emphasis on fuel conservation efforts. These efforts have had some impact on

control system design, primarily in the area of shaft speed/propeller pitch scheduling in gas turbine-controllable pitch propeller ships. The schedules have been effected in low, medium, and high speed areas.

Low gas turbine-CPP ship speeds have traditionally been obtained by maintaining a low, fixed shaft speed, and adjusting propeller pitch as necessary to obtain the desired ship speed. A more efficient approach, suggested by Rubis and Harper[(6)], is to hold engine fuel flow constant at idle while adjusting propeller pitch. While shaft speed will drop as higher pitches are used, the increasing efficiency of the propeller with pitch will produce an increasing ship speed. For ship speeds above that associated with propeller at design pitch and idle fuel flow, the propeller can be maintained at design pitch and engine fuel flow increased appropriately. The increased fuel results in a higher shaft speed and thus a higher ship speed.

Medium ship speeds on two-shaft COGAG-CPP ships have traditionally been attained by running one engine per shaft, with each engine producing a low output power. A more fuel-efficient method is to run a single engine at higher power, while trailing the unpowered shaft. Trail shaft operations impose a much higher torque on the driving shaft than normal twin-shaft operation does, and thus force the driving gas turbine's power turbine to operate far from its most efficient point. Some fuel savings are realizable by conducting trail shaft operations at propeller pitches below design.[(7)] The reduced pitch restores power turbine operation to its most efficient point.

High ship speeds are normally obtained with propellers at design pitch. Fouled hulls, heavy ship loads and similar factors frequently combine to increase the torques associated with design pitch operation. These increased torques tend to drive power turbine operation away from its most efficient point. Slight reductions in pitch can restore efficient power turbine operation, and yield a modest fuel saving[(7)].

We expect future gas turbine-CPP ship control systems to use Rubis' constant fuel flow schedule, and to have specific provisions for efficient trail shaft operations. Slightly farther in the future may be a control system feature which automatically adjusts pitch to minimize fuel consumption.

CONCLUSION

The U.S. Navy is currently not emphasizing the use of electronic centralized monitoring and control systems as manning reduction tools. Manning concerns have been overshadowed by other considerations including habitability, vulnerability, maintainability, training capability, reliability, and ship energy efficiency, each of which has an impact on control system design.

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AUTOMATION IN SHIP CONTROL AND MONITORING SYSTEMS ON SURFACE SHIPS OF THE GERMAN NAVY

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ABSTRACT

This paper renders a short survey on automation applied on ships of the German Navy.

Based on the experience with systems already realized, a planning procedure has been elaborated by means of which a new concept for automation of future ships could be developed.
An essential objective of this concept is - on the one hand - the achievement of an optimum allocation of functions to the operator and the equipment as well as the purpose-related realization of advanced technologies.
On the other hand system-adapted automatic devices are to be applied to achieve a homogeneous automation within the total ship's engineering area.

Application of decentrally arranged computers of certain structures simultaneously creating an adequate and cost-effective system redundancy is a decisive component of this concept.

INTRODUCTION

Encouraged by the developments in merchant shipbuilding and the obvious progress that had been made in the field of electronics, the German MoD decided at the beginning of the 60's to test automation in certain areas of ship technology. This paper discusses the evolution of automation of control and monitoring systems in the German Navy. Although automation can be applied to many areas of a ship, this paper deals only with the ship's engineering automation.

The first ship to employ automation, was an appr. 3400 tons, diesel driven mine transporter, which was commissioned in the mid-sixties. This ship was fitted with automized electric power supply systems and a data processing system which also monitored the propulsion plant. Despite initial difficulties - i.e. reticence on the side of the user in the face of the new technology, training problems and teething troubles especially with regard to the components - experience showed that all in all this was a step in the right direction. It soon became evident that the automatic sequence of certain machinery functions and, above all, the monitoring tasks performed by automatic devices removed pressure from the ship's personnel or even led to a reduction in personnel. However, experience also showed that there was still a long way to go before automatics could meet system conditions or before the hardware could be adapted to the environmental conditions which prevail on board navy ships. One example was the frequent initial failure of sensors due to vibrational stress. Fortunately these problems have been overcome to a great extent these days.
Even during the evaluation of the test results of the automation on

board the mine transporter, the situation with regard to the planning of new ships was already changing. The subsystems of the ship's engineering area to be fitted into new ships were becoming more complex and as a consequence, the control and monitoring effort had increased considerably.
This would have meant increasing the ship's complement. The consequences of such action are well known and do not need to be detailed here. And so the question was no longer whether to introduce automation or not, but how, and in what areas automation should be applied usefully.

APPLICATION AND EXPERIENCE ON FAST PATROL BOATS AND FRIGATES

The next step along the road to automation was the FPB 143, a 390 t fast patrol boat. Planning work began at the end of the sixties; the commissioning of the first boat took place in 1975. The boat is fitted with four diesel engines for propulsion, fixed-pitch propellers, and four diesel electric generator sets. Fig. 1 shows the layout of the control and monitoring concept for the propulsion and electric power plant.

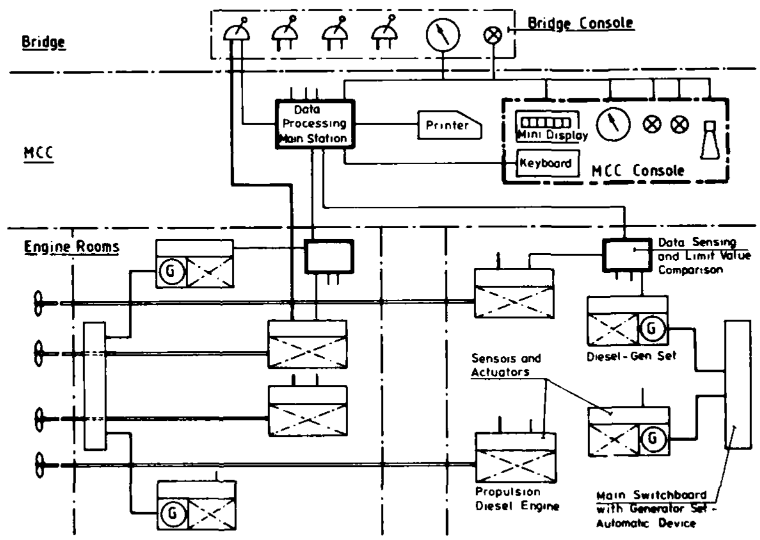

Figure 1. Principle Structure of the Control and Monitoring System FPB 143 Class

The philosophy behind the ship's operation can be summarized as follows:

- propulsion plant operation from the bridge, with monitoring from the Machinery Control Centre (MCC);
- electric power plant operation and monitoring from the MCC;
- important ship auxiliary systems and damage control operation as well as monitoring from the MCC.

In the case of failure of the central control and monitoring systems within the MCC all systems can be operated locally.

The propulsion plant is controlled pneumatically, i.e. analog. The automation systems are analog systems for the most part with discrete building modules in accordance with the state of technology in those days.
Today it can be said that this concept proved very functional for the ship.
Further progress is being made with the Frigate 122 project, a 3500 t ship which is presently under construction. The planning work for this ship began in the first half of the seventies.

A much more complex propulsion concept is involved in this case; it is a CODOG arrangement which comprises 2 MTU diesel engines and 2 GE LM 2500 gas turbines as well as controllable-pitch propellers (CPP). The extent of automation in the electric plant, the ship auxiliary systems and the damage control area is also considerably greater. This is shown in Fig. 2.

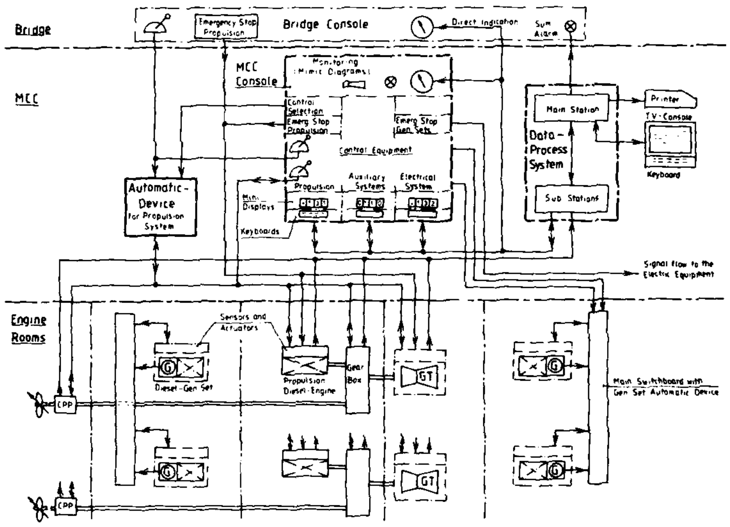

Figure 2. Principle Structure of the Control and Monitoring System Frigate 122 Class

In contrast to the FPB 143 the automation of the Frigate 122 is more extended in the following areas:

- operating the propulsion plant automatically from the bridge or from the MCC;
- operating and monitoring the main electrical distribution system automatically from the MCC;
- automatic starting, operation, stopping of propulsion diesel

engines and gas turbines;
- setting optimum propeller pitch in relation to speed;
- load transfer from diesel to gas turbine and vice-versa;
- central monitoring of all important operating data with automatic alarm actuation whenever threshold values have been exceeded;
- application of a monitoring screen.

Besides the automation of the operation of the electric power supply system the following functions are also automatic on Frigate 122:

- automatic switch-on of additional generator sets when load limits are exceeded;
- automatic switch-off of unimportant consumers of electricity at staggered intervals in the case of failure of the generator sets.

In the area of ship auxiliary systems some functions are automatic, for example:

- room air-conditioning
- fresh water generation.

With regard to damage control rooms which are exposed to danger by fire or water are provided with automatic monitoring systems. This system is designed in such a way that a signal is released that can quickly identify the location of alarms or failures.

Generally, signal processing is still analog. Analog/digital converters are provided only for displaying individual data that is called up.
The automatic monitoring and control devices for the propulsion system are fitted with microprocessors, which have an extensive self-diagnosing system and work on the fail-safe principle. Besides these, other devices made of discrete building modules have also been used.

The MCC is fitted with mini-displays for the operator's use whereas the ship's technical officer has access to comprehensive system data on a larger display screen.

These two display systems are decoupled from each other and therefore constitute a redundancy. All monitoring and remote-control functions are thus performed centrally in the MCC. The engine rooms need to be entered only for:
- preparing for sea,
- maintenance purposes, and
- in cases of emergency, for local operation.

ACTIVITIES IN THE COURSE OF FURTHER DEVELOPMENT

The main objective of automation is an optimum task allocation to the operator and the equipment under consideration of the operational conditions.

The present state of automation still comprises different automation levels and a wide range of automation device technology. Besides automation systems, that utilize microprocessors, pneumatic control devices are also used.

This state of technology has a number of negative consequences, such as:

- different functional principles
- extremely different training requirements
- large number of functions, still manually performed in some parts
- restricted standardization possibilities
- large quantities of spare parts required
- rather high prices per piece as series production is hardly feasible

To achieve the afore-mentioned main objective, i.e. optimum task allocation, an analysis should be carried out to find the answer to certain important basic questions. This is required before a complete concept can be elaborated. The following questions from a specific navy point of view must be clarified:

- how can the present operational functional sequences be optimized?
- for which systems is an automatic device advantageous?
- what consequences does the rearrangement of functional sequences have on the tasks to be performed by the operator requiring the corresponding capabilities?
- what individual requirements have to be met by the automation concept?
- what weighing factor is attached to the different and sometimes contradictory individual requirements?

Detailed knowledge of the functional sequences of the different activities within the ship's engineering area is mandatory for optimum application of automation.

For this reason it is necessary to define these activities and analyze the different functions in the light of the comprehensive task to be performed within the ship's engineering area. In keeping with this objective, suitable sequences are then sought, for which automation devices can be applied.

This process is repeated continually until the objective is achieved, or until technical impossibilities are encountered which put an end to the search.

This analysis will definitely require a work effort that should not be underestimated since the access to the corresponding basic source documents is not in every case immediately available. Moreover, elaboration of the required functional procedure plans may adopt a large extent, and this should be carried-out extremely thoroughly.

Experience has shown, however, that these activities are inevitable if a system-specific planning work is to be performed.

Due to the sophistication of the systems in questions, as well as the variety of functions and their interrelations simple rough estimations are likely to lead to misinterpretations causing an erroneous lay-out.

Fig. 3 (see next page) shows a simplified functional procedure to achieve certain goals, showing, for instance, the procedure to achieve a potential personnel reduction.

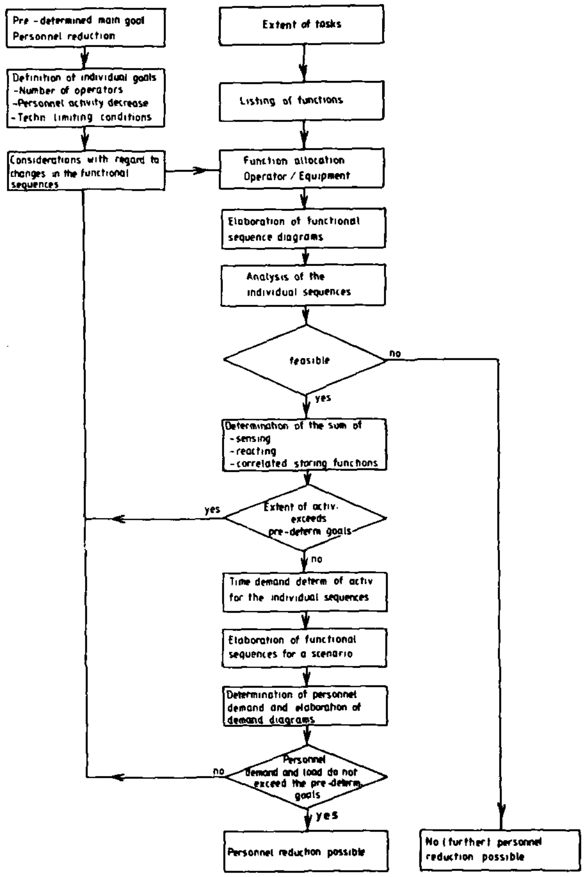

Figure 3. Functional Procedure to Achieve Certain Goals

As already mentioned before the starting-point must be a comprehensive analysis of all actions occurring on board. As initial activity it is worthwhile working out a functional tree with all the different actions and their allocation within the hierarchy of ship operation.
Fig. 4 (see next page) shows the development of this allocation with the power plant and its electric generating plant highlighted as an example.

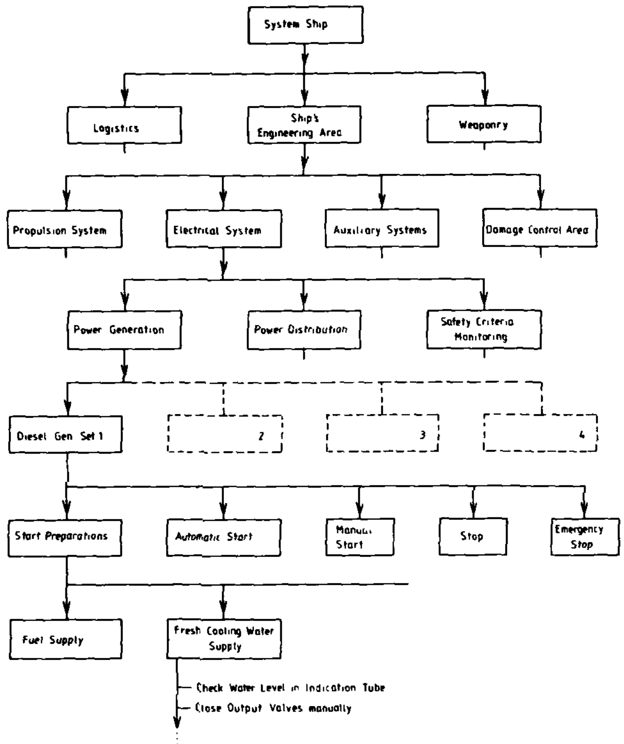

Figure 4. Functional Tree

Systematic work leads to a diagram of the results of this analysis. This diagram offers quick and extensive information for taking decisions on whether functional sequences can or should be automated and in what way. It is useful to display this information on a matrix as in Fig. 5 (see next page).

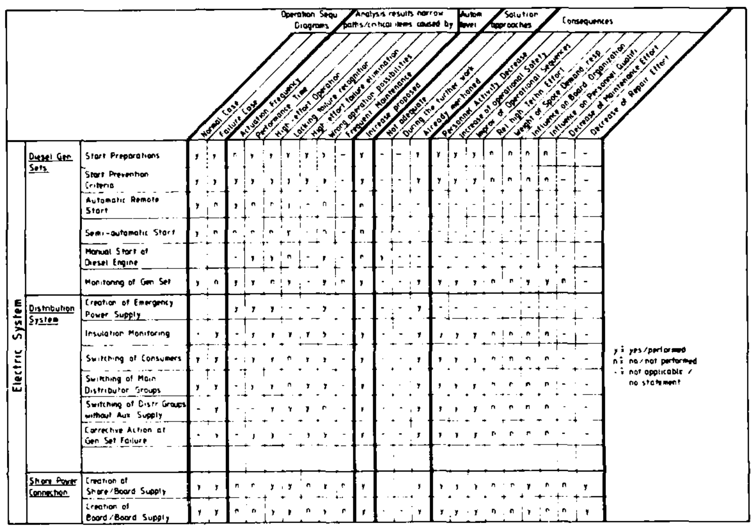

Figure 5. Excerpt from: Matrix of Items to be Analyzed

Besides the question of what should be automated, the question of how this can be done is, of course, also important. There are many different individual goals behind automation and different users most likely give different priorities to these.

The afore-mentioned analysis resulted in a breakdown of the different individual goals into six categories. In order to ascertain those goals which were to determine the automation design, the individual goals were compared in pairs. For each comparison the question is posed repeatedly as to whether one goal is more important than the other and, if so, how much more important. Eventually, all individual goals have been compared with each other. (1) (2)

A simplified diagram of this evaluation is shown in Fig. 6 (see next page).
The results are best shown in the form of a bar chart as shown in Fig. 7 (see next page).

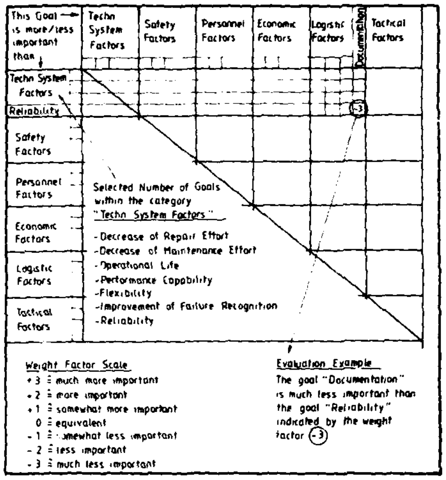

Figure 6. Weight Factor Matrix (schematic)

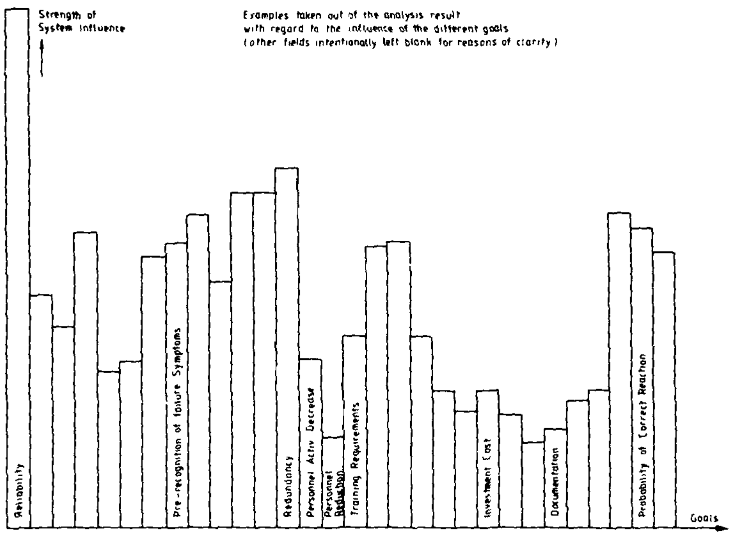

Figure 7. Bar Chart

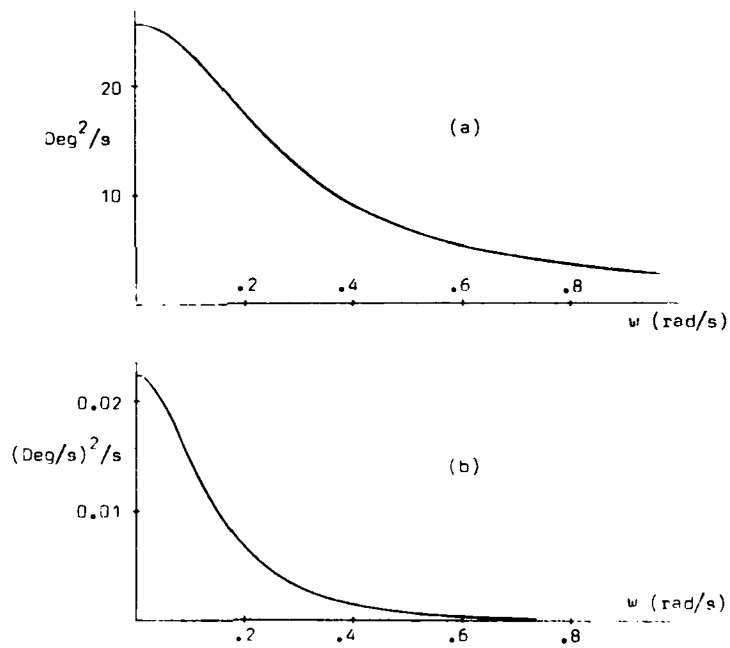

Fig (2): Spectral density estimates of the applied rudder angle (a) and ships yaw rate (b) when stimulated by PRBS at 16 knots as derived from MEM analysis.

shown in standard texts (10) that:

$$H(j\omega_k) = \frac{S_{xy}(j\omega_k)}{S_x(j\omega_k)} \qquad \ldots\ldots\ldots\ldots \qquad (3)$$

$$\eta^2 = \frac{\tilde{S}_y(\omega)}{S_y(\omega)} \qquad \ldots\ldots\ldots\ldots \qquad (4)$$

where $x(t), y(t)$ are system input and output, $H(j\omega)$ is the frequency response, S_x, S_y, S_{xy} are the relevant spectral density functions and η^2 is the coherence function.

The coherence function checks the reliability of the frequency response estimate b

This leads us to two important pieces of information, fi answer to the question as to what functional sequences are tc tomated, and second, the basic principles of the automation l With this in hand, the characteristics of a homogeneous auton concept are to be described. This process must, of course, ta account the hardware available at the time of planning for th zation of the concept. Up to now the technically feasible pos ties offered by automation have not been used to the full ext

Goals of Automation

Individual goals within the afore-mentioned main objecti optimum task distribution are:

- reduced number of operating personnel required
- reduced stress on operating personnel
- prevention of incorrect operation by the personnel
- quicker reaction in critical situations
- improved performance of equipment and engines
- more selective maintenance activities to reduce the ove maintenance effort
- adequate presentation of the technical functions and pı dures executed on board
- extended introduction of correlated monitoring to enabl trend analysis, i.e. recognition of symptoms indicating development of potential failures (3)
- standardization of software and hardware
- optimization of the technical and financial effort invc in automation
- more economical - e.g. fuel-efficient - operation of pc plant

DESCRIPTION OF THE AUTOMATION CONCEPT TO BE REALIZED

To achieve the afore-mentioned goals the following automa concept was elaborated:

The ship as a "system" is structured according to the fol three areas and its apertaining central operating and monitori tions:

- Ship's command - Bridge
- Ship's engineering - MCC
- Weaponry - CIC (Combat Information Center)

Fig. 8 (see next page) shows the relationship between the areas. As noted earlier this paper deals only with the ship's neering area. The MCC represents the central decisive item wit this area. This is applicable to both, the control devices as monitoring of components and subsystems. Moreover, a different has been made in this concept between the operator-related and equipment-related functions.

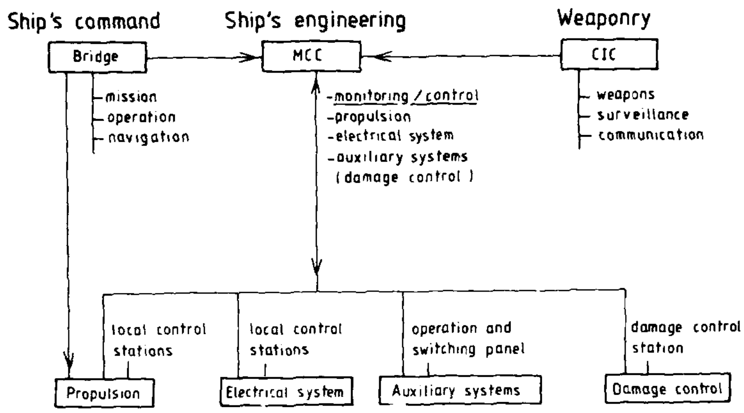

Figure 8. Structure of the Ship as a System

Similar to current procedures on modern ships control of the components for propulsion is also in the near future likely to be performed primarily from the MCC, but definitely with increased assistance of programmed automatic devices.
Dependent on propulsion concept and mission it has to be decided whether these automatic devices comprise only start/stop programs or also load adaptation and load transfer programs or programs for combination of functions, resp., such as allocation of propeller-pitch and speed to certain ship velocities or maneuvers.
The structure of this control concept will subsequently also be discussed together with the application of computer stations.
Moreover, there are considerations with regard to an extension of automation, especially in view of a combination of functional procedures related to navigation with those of the ship's engineering functions. These considerations are especially related to the design concept of smaller ships, such as FPB's.
It seems, however, to be too early to report on results or partial results already now.
Monitoring is effected at present via a centrally arranged data processing system, that supplies the operating personnel with the necessary information. The state of technology here includes:

- analogue instruments,
- mimic diagrams consisting of luminous diodes and additionally,
- mini-displays.

The goals mentioned earlier, which imply the effective employment of a reduced number of operators, are the basis for the development of ship automation in the future. This requires the breakdown of operation data display into two levels:

- simplified mimic diagrams on mini-display for quick information and
- larger screen displays for detailed information.

Furthermore, intervention on the part of the operator in the sequences in progress are to be of a superordinate nature only, e.g. emergency switch-off activities.
Subordinate operator activities with regard to the functional sequences should not be allocated to the operator but performed automatically, e.g. switch-off procedures of less important consumers due to an overload condition of the power supply.
Combining information displays with operating elements thus offers a practical solution. The mimic diagrams contain mainly digital information.
Keyboards are provided in order to permit arranging the sequence of data displays (e.g. all essential data on status of a propulsion engine). In this arrangement failures and alarm messages have priority and will be given special preference in the transfer and indication process.
The data display is also intended to offer decision aids for switch actuation and to contribute to the training of personnel by means of simulation programmes.
Fig. 9 shows a diagram of the MCC operating and monitoring console of a smaller ship of about Corvette size for which the planning has just been completed.
A large number of the conditions mentioned before have been realized in this concept. The console is designed for one-man-operation under normal conditions but in the case of a failure or for special operational conditions a second operator can render assistance.

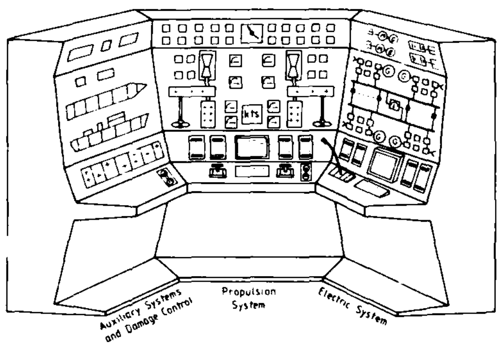

Figure 9. Arrangement of operational Elements for centralized Monitoring/Control

The idea behind the new concept is to arrange the whole technical equipment for automation - i.e. for control and monitoring - decentrally. Fig. 10 (see next page) shows the basic arrangement of such a system.
Several autonomous computer stations (a....n) based on microprocessors will be locally arranged as close as possible to the connected systems, i.e. within the engine compartments; they comprise control and monitoring devices which are functionally separated.

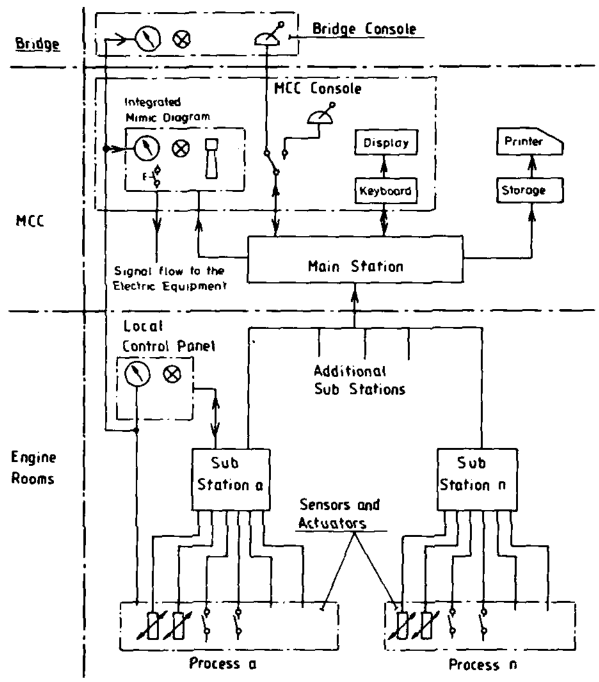

Figure 10. Principle Structure of the Automation System

The computer stations must - at least for the control functions - perform the allocated processes in on-line operation; these might, for instance, be processes within the diesel generator power supply or the propulsion system.
For a coordinating computer in the MCC, off-line operation would, however, be permissible.
Data preparation and pre-processing will be performed within the decentralized autonomous computer stations. The coordinating computer in the MCC enables the operator to correspond with the individual computer stations and also organizes data storage.(4)
It has to be defined whether the decentralized computer stations will be coupled to the coordinating computer within the MCC by means of a circular data bus system or whether a hierarchic structure should be provided dependent on project-specific requirements. These approaches each have their advantages and disadvantages.(5)

In the case of a malfunction of the computer in the MCC or of any disturbed information flow between the MCC and the individual computer stations, the autonomous computer stations will continue to operate self-supporting, i.e. based on a pre-stored programme. Consequently, the corresponding machinery systems being controlled do not

fail due to the above-mentioned malfunctions. Control and monitoring of the individual machinery systems would then be performed by means of the still properly functioning computer stations, i.e. using partially automatic devices. For this purpose, the conventional local control stations must be combined with the autonomous computer stations. This would, for instance, be achieved by locating the computer stations within the local control stations.
Manual operation using conventional technology is to be provided locally for systems whose functions are important for the operational capability of the ship and whose operation must be maintained even in the case of a failure of the automatic devices.
Location of automation equipment within the engine room will naturally require an improvement of the present state of technology. Increased ambient temperatures and the aggressive oil-containing atmosphere create particularly difficult problems.
A further requirement in that the 24 volt d.c. power supply for the automatic devices and peripheral equipment be continuously available, is met by the standard ships 24 volt d.c. system being supplemented by a battery back-up system.
A high level of automation always entails the dangerous risk that the operation of certain systems or even the mission of the total ship may be negatively affected if an automatic device fails. This should be given special consideration for a navy ship where:

- reliability and
- operational availability

are of vital importance.
These requirements necessitate making the automatic devices reliable by means of certain selective measures, i.e. by providing redundancies. Arrangement of the control/monitoring areas at different locations is due to this aspect.
The following considerations apply when designing future automation concepts:
The two main functions control and monitoring carried out in the individual computer stations will be sub-divided as follows:

a) permanently required functions (e.g. required whenever the ship is at sea or the power plant is in operation)
b) functions which are necessary, but which can be carried out to a limited extent with reduced computer capacity (e.g. determination of one common exhaustgas temperature value for all cylinders of a Diesel engine instead of measuring every individual value. If the common exhaustgas temperature exceeds a maximum value a reduction of the injected fuel quantity has to be accomplished.
c) functions which are not necessarily required, i.e. which can be done without in the case of failure (e.g. training simulation).

All individual computer stations should be designed in such a way that they are capable of exclusively performing functions a) and b) in the case of computer component failure; at that time, the number of functions defined by b) will be reduced. For this purpose the individual sections of the computer stations must, however, be able to perform additionally the functions of defective computer sections or adjacent stations in a reduced form. The uneconomic design of duplicated computer stations will thus be avoided.
These considerations are to be clarified using a possible concept as an example, showing the single unit version of a redundancy concept. See Fig. 11 (next page).[6]

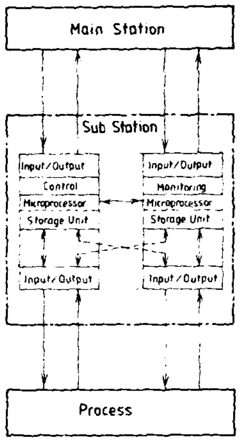

Figure 11. Redundancy Concept of the Automation System

Every computer station is allocated either to one or to several particular processes depending on the required memory capacity. Usually, control and monitoring functions are separated within this computer station. The control section as well as the monitoring section are, however, slightly overdimensioned for the following reasons:

Should, for instance, a fault occur affecting operation of the monitoring section the essential monitoring functions would be additionally performed by the control section. The control section must, of course, be designed for this "emergency operation", i.e. the required programmes must be pre-stored in fixed-value stores. A similar arrangement is also to be provided for failure of the control section.

For reasons of logistic advantages the sub-stations should be provided with a capacity which

- permits application of these sub-stations for projects of various sizes, but in their basic elements also for different processes.

On the other hand

- a limitation of the number of types can be achieved due to several equivalent assemblies.

The design of the internal power supply elements, the selfmonitoring system and the basic programme sequence may be the same for all sub-stations.

At the moment we consider 12 to 16 sub-stations to be adequate for a medium-sized ship, that means a corvette or a frigate. In view of the existing technical possibilities we hope to achieve an optimum allocation of tasks between operator and equipment. The allocation of tasks will have consequences on the ship's operational concept. Future automation systems will be designed according to consistent basic principles; failures of minor importance in the engineering area will be selectively switched-off and immediately by-passed automatically. The operator need only intervene in critical situations. On

the other hand, the consequences resulting from the operators attention being distracted should be avoided by indication of these "second-rate" failures during uneventful periods.

Furthermore, simulation programmes could be run off which have the added advantage of training the operator. These programmes are, however, interrupted immediately when genuine failures occur. A simplified version of the intended structure is shown in the following figure.

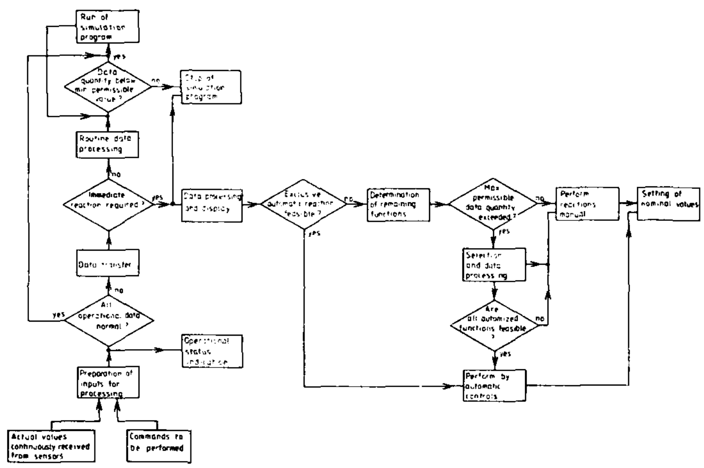

Figure 12. Structure of the intended Central Monitoring/ Control within the Ship's Engineering Area

SUMMARY

The shi,› automation concept presented here is based on today's technology; it will, however, only be able to be realized to its full extent in the future. During the present planning work some further steps to increase the extent to which ships are automated can be taken with limited technical and operational risks and at reasonable costs.
All in all, we expect to achieve optimum operational capability in the German Navy with the new concept, especially with a view to typical navy ship problems (e.g. work effort involved in cases of damage). Furthermore, with the aid of the trend analysis presently being developed, maintenance efforts can be rationalized by dividing the work load between on-board and shore-based mobile maintenance personnel.

It is also hoped that standardization will reduce costs during the operational phase of the ship. Last but not least, a balance must be attained in future between technically feasible solutions and the involved effort (e.g. cost auf automation equipment).

From our point of view these goals can only be achieved if a homogeneous automation system is designed for the ship's engineering area. This means that the definition of the system and the design of that which is in the "black boxes" must be consistent.

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AN APPROACH TO AUTOPILOT DESIGN BASED ON NONLINEAR SHIP MODELS WITH UNCERTAIN PARAMETERS

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ABSTRACT

It has long been established that the dynamics of a marine vessel can be represented adequately only by resorting to a nonlinear model which includes the speed, sway and yaw variables of up to third order of a Taylor's expansion of the hydrodynamic excitation forces and moments. Equivalently, a representative linear model can be derived with a transfer function which relates yaw to rudder angle having coefficients which are functions of these variables and which are therefore time-varying or, more correctly, are functions of the manoeuvre in hand. If the autopilot is to cater for speed changes and the execution of large manoeuvres then a constant coefficient ship model is patently unsatisfactory.

Two obvious approaches present themselves: to adopt an adaptive scheme which involves the identification of an instantaneous model and the assumption of some control law; or to maintain conceptually that the nonlinear variations are simply *manifestations of a time variation of* parameters which are essentially realizations of nominally constant coefficients with a large tolerance span. In the latter case, the loop function can be designed to effect sufficient reduction in sensitivity of the nominal ship response to all parametric variation and to low-frequency environmental disturbance.

Investigations have been carried out to compare the effectiveness of two such controllers: a self-tuning variety and one based upon sensitivity design. It was found that the latter was superior as a controller per se but that it was decidedly inferior in the minimisation of rudder activity arising from sea-state as a consequence of the very wide loop bandwidth necessary to maintain the required reduction in sensitivity. To resolve this difficulty, consideration has and is being given to means of reducing the extent of the parameter-value ignorance by the investigation of loop-bandwidth adaptation and to the application of inverse nonlinear cancellation control methods.

The paper presents the findings to date and outlines the philosophy of approach adopted for the on-going investigations.

INTRODUCTION

It has been reported elsewhere (1) that the instantaneous linearized model of a manoeuvring ship can vary considerably throughout the manoeuvre and that if the specifications of the autopilot call for repeatability of response irrespective of the magnitude of the rudder demand it is known that such a reduction in sensitivity can only be brought about by an excessive increase in the loop bandwidth (2). However, the implementation of wide bandwidths in the marine situation results in the feedback of amplified sea-state noise with the likelihood of consequential satur-

-ation of the rudder servo as can be seen from equation (1) which expresses the transfer function relating plant drive p(s) and sea-state noise n(s) and which is true for frequencies above the cross-over of the loop function.

$$\frac{p}{n}(s) \cong L(s)/P(s) \qquad \ldots\ldots\ldots\ldots \qquad (1)$$

where L(s) and P(s) are transforms of the loop and plant (ship) functions respectively.

At high frequencies the amplitude ratio of equation (1) can be very large, certainly of the order of 40 db, over a wide frequency range. Rudder demands which fluctuate rapidly over wide ranges are undesirable from the point of view of the integrity of the hardware and will result in uneconomic propulsion performance.

The dilemma which confronts the designer is that reduction of the loop bandwidth will give rise to a worsening of the ability of the closed-loop system to counteract the effects of the variation of the ship dynamics. Such would be the case if the feedback signal was filtered of the offending sea noise. However, a much lower loop bandwidth could be tolerated if the varying dynamics could be tracked via estimation procedures throughout the transient periods of ship motion. Investigations have been carried out and are discussed in the next section on the identification of a ship whilst it was manoeuvring but with little success. It became apparent that the dynamical variation was substantially complete before the variance of the estimates had fallen to values which were better than that known a priori from the predicted tolerances of the linearized model (1).

An alternative to the use of estimation procedures is obviously the reduction of the variation of the individual parameters of the ship model. If the stated variation of the parameters is indeed correct (ie, not simply worst-case estimates or the result of ignoring correlation between parameters or due to a reliance on simplifying assumptions, each of which might indicate a greater variational range) and if the system is linear, then there is no way other than by the use of feedback (provisionally ruled out by the presence of noise) in which the variation can be reduced. However, the ship is <u>not</u> a linear system and the variation referred to in reference (1) is arrived at only by considering the changes which occur in a hypothetical linear model in order to match the nonlinear responses of the ship. The possibility therefore exists for the reduction of the observed variations by the application of inverse nonlinear compensation. Indeed, if there were no variation of the true parameters of the actual nonlinear ship then there would be no requirement at all for the use of feedback other than to mould the form of the transient response required. The variation which does occur in the nonlinear model arises as a consequence of the divergence between the nominal system model as conceived by the designer and the real ship, which springs from the designer's ignorance of the ship parameters and the hydrodynamic variation under manoeuvring conditions. That is, his parametric values are only estimates and the hydrodynamic derivatives which he may employ have been obtained from captive-model tests and/or approximate analysis (3,4). It is to be expected, nevertheless, that the ignorance from these sources will be less than the huge range of variation which must be allowed for satisfactory linear-nonlinear matching.

ESTIMATION OF RAPIDLY CHANGING DYNAMICS

It was suggested in the previous section that loop adaptation might offer a means of solving the ship control problem during transients, whereby the loop would be modified according to the deviation of the instantaneous model from that of the nominal. Of course the pole-shifting self-tuning algorithm attempts a similar function (5,6), but for loop adaptation it was envisaged that it would not be necessary to rely on accurate estimation. That is, only sufficient predictability would be required to reduce the degree of uncertainty to levels which would limit

significantly the loop bandwidth and hence the feedback of noise.

To this end it was necessary to investigate the ability of estimation algorithms to handle the changing dynamics of a manoeuvring ship and, to test effectively the efficacy of the procedure, data was sought from sea trials conducted aboard a vessel of the Royal Navy which would inevitably include extraneous noise from environmental sources. The data obtained consisted of analogue tape recordings covering ship motion with demanded rudder angles determined by PRBS, sinusoid and step change sources. The following discussion refers to the identification of the nominal ship model whilst moving in a straight line at 16 knots using measurements obtained from PRBS tests involving an amplitude of $\pm 8^{\circ}$, a bit-period of one second and a source register of seven bits.

Spectral Analysis

Preliminary identification of the model type and order along the lines of Box and Jenkins (7) had indicated that white noise filters to predict resulting rudder angle and yaw rate signals would be of autoregressive form and of orders five and six respectively. Analysis of the data using the Maximum Entropy Method (8), MEM, together with the Final Prediction Error (FPE) criterion of Akaike (9) did not indicate a decisive selection of model order, as shown in figure (1), with little distinction being made between models of order five and higher for the rudder angle data and between models of order six and higher for the yaw rate data.

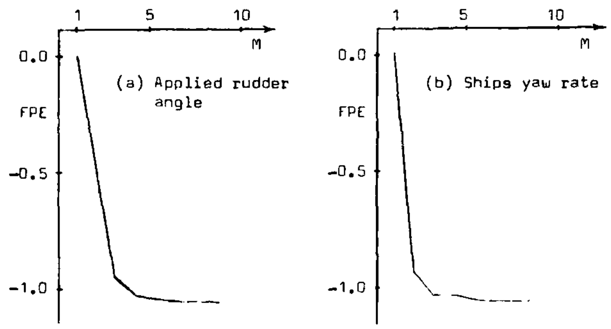


Fig (1): Variation of the logarithm of the normalised FPE as a function of the model order, M, for the rudder-angle and yaw-rate data.

Figure (2) shows the expected power density spectra of the two processes on the assumption of 5th and 6th order models respectively and by manipulation of the z-transformed noise models into continuous form the transfer function of the ship is found, after reduction, to be:

$$\frac{r}{\delta}(s) = \frac{-0.0297(1 + 2.592s)}{(1 + 6.74s)(1 + 2.10s)} \qquad \ldots\ldots\ldots\ldots \qquad (2)$$

where r is the ship yaw rate and δ is the applied rudder angle.

In an attempt to confirm the estimation of equation (2) DFT methods were employed to determine spectral and cross-spectral density functions for the above data. It is

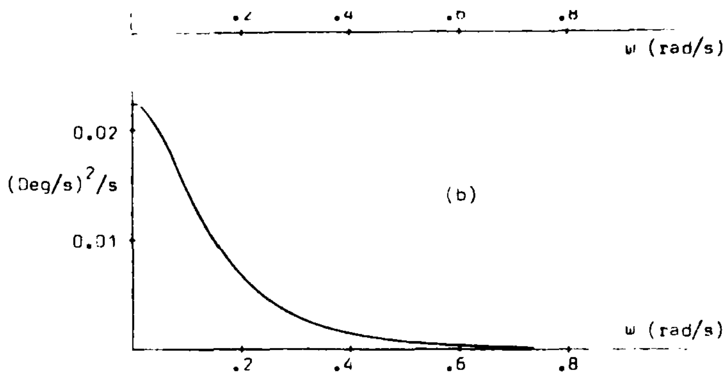


Fig (2): Spectral density estimates of the applied rudder angle (a) and ships yaw rate (b) when stimulated by PRBS at 16 knots as derived from MEM analysis.

shown in standard texts (10) that:

$$H(j\omega_k) = \frac{S_{xy}(j\omega_k)}{S_x(j\omega_k)} \quad \ldots\ldots\ldots\ldots \quad (3)$$

$$\gamma^2 = \frac{\tilde{S}_y(\omega)}{S_y(\omega)} \quad \ldots\ldots\ldots\ldots \quad (4)$$

where $x(t), y(t)$ are system input and output, $H(j\omega)$ is the frequency response, S_x, S_y, S_{xy} are the relevant spectral density functions and γ^2 is the coherence function.

The coherence function checks the reliability of the frequency response estimate by comparing measured S_y and calculated $\tilde{S}_y$ spectral functions and should, on the assumption of undistorted measurements, have a value of unity at all ω_k. The results for the PRBS data are shown in figure (3) in comparison with the MEM prediction. The coherence function values would suggest that the results are none too reliable, especially in the region of 0.6 rad/s. There is, however, some degree of agreement between the MEM and DFT amplitude ratio estimates which would suggest that a (II,I) model for the yaw-rate to rudder-angle dynamics is not unreasonable.

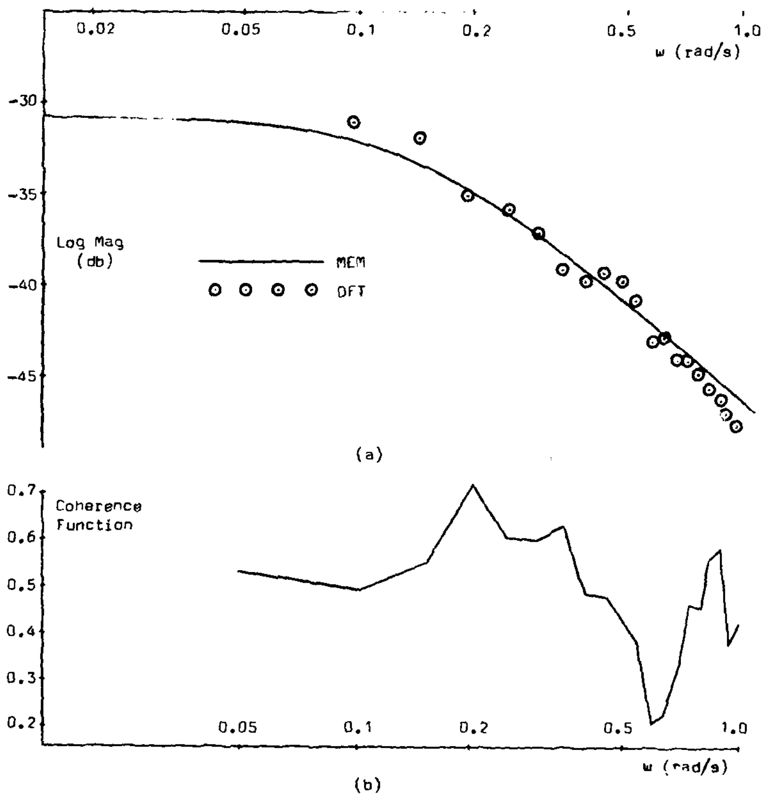


Fig (3): Estimated yaw-rate/rudder-angle frequency response of ship at 16 knots obtained from PRBS data of 2048 points with a sampling period of 0.5s.

Least-Squares Estimation

The PRBS data was again used for the ship moving at 16 knots and the recursive least-squares rout.ne employed to estimate the ship model which, according to the preliminary investigation, should be of second order and take the form:

$$\frac{r}{\delta}(z^{-1}) = \frac{z^{-1}(b_0 - b_1 z^{-1})}{1 - a_1 z^{-1} - a_2 z^{-2}} \qquad \ldots\ldots\ldots\ldots \quad (5)$$

Satisfactory estimation was achieved only after filtering the yaw-rate data using a first-order digital filter of one second time constant, when the variation of the

individual coefficients was restricted to less than $\pm$ 9%. On conversion to the continuous form, it was found that almost exact cancellation occurred giving rise to the reduced model:

$$\frac{r}{\delta}(s) = \frac{-0.0417}{(1 + 14.88s)} \quad .... \quad (6)$$

Even small changes in the z-locations of the system poles were found to generate large variations in the parameters of the continuous function such that the tolerance on the gain of expression (6) was $\pm$ 34.3% whilst the time constant could vary through -20.3% to +33.7%.

Although the tolerances cited were much greater than expected after 500 seconds into the test, they are considerably less than those used for the ship when designing the loop function on the basis of sensitivity reduction.

Least-Squares Estimation over Transient Period

The analyses carried out above were primarily concerned with the estimation of a pseudo steady-state model of the ship whilst unperturbed and showed that although the coefficients of the discrete model could be estimated to within an acceptable degree of uncertainty, the variation of those of the continuous model was not insignificant. In this section, however, attention is directed towards the computational time required for the estimator to arrive at asymptotic values of the model coefficients.

Two sets of data records are used for this purpose. Firstly, the PRBS data for the ship moving at 16 knots and, secondly, data obtained when the ship was excited by an applied sinusoidal waveform at a frequency of 0.07 Hz and amplitude 10^{o}, again with the ship moving nominally at 16 knots. The frequency was selected as being that which most nearly approached the condition of persistently exciting.

Figure (4) shows the estimation achieved over fifty seconds of the PRBS data with a sampling period of 0.5 second. Prior to 10 seconds, the estimated values fluctuated widely. Whilst the denominator coefficients settle to some extent within 15-20 seconds, those of the numerator take at least 50 seconds. It was found upon examination of the frequency response records, now sampled at 10 Hz, that stabilization of the estimates could not be achieved in under 200 seconds (see figure 5) and that it was noticeable again that it was the numerator terms which settled most slowly.

Data was then examined which had been recorded of the ship motion upon the application of a step-change rudder demand of 8^{o}. Again there was an enormous fluctuation of the estimates up to the time when the ship was entering its steady-state of circular motion. Repeated off-line processing of the transient-data records, such as noise modelling, did not result in any satisfactory improvement.

As an alternative approach, the data was processed manually with the mean achieved yaw rate and the equivalent first-order time constant determined visually. Although a first-order model was sought, it was apparent from an examination of the initial response that a second-order model would be appropriate. Visual examination of the response highlighted a pronounced sinusoid of period 20.6 seconds whilst the ship was in the turn, which reduced to 14.8 seconds on pull-out. During this latter stage also, the amplitude of this secondary motion was seen to increase by at least 100%. Further examination revealed that this oscillation was a roll-related phenomenon which resulted in markedly different estimates for the time constant of the ship as follows:

(a) Model during initial response:

$$\frac{r}{\delta}(s) = \frac{-0.033}{(1 + 12.14s)} \quad .... \quad (6a)$$

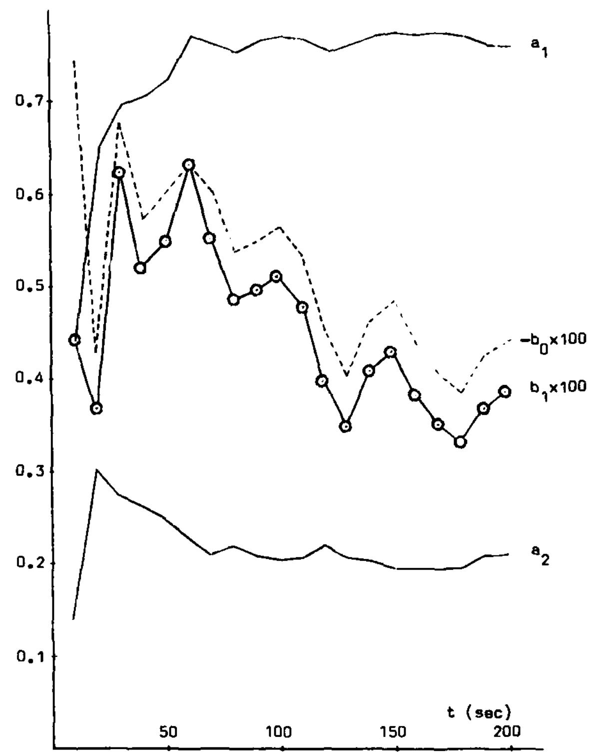


Fig (5): Least-squares estimation of the coefficients of the pulse transfer function of the ship obtained by the application of a sinusoidal rudder demand of 0.07 Hz, with a sampling period of 0.1 second.

-ointing even with off-line processing. It was obvious however that estimation of the ship model over such a short period of excitation was out of the question. Contributory factors to the failure are undoubtedly the magnitude of the disturbance noise present on the yaw-rate signal and a significant roll perturbation. Additionally, with rapidly changing dynamics, it might well be that the mode of excitation is inadequate.

It is considered therefore that RLS is inappropriate as a method of estimation in the case of the nonlinear and non-stationary ship when the function of the identification is the tracking of the ship model during the comparatively short transient period following the initiation of a manoeuvre.

INVERSE NONLINEAR COMPENSATION

It has been suggested in the introduction that serious feedback noise problems may result should the allowance for nonlinear behaviour require a large range of variation of the equivalent linear plant. The objective of this section is to consider one possible means of avoiding this situation, and one which is increasingly feasible given the availability of digital hardware, by the use of the hybrid operation of both linear and nonlinear controls. The use of the latter effectively enables the plant to be considered as linear time-variant (LTV) whilst the linear control acts on this modified plant to approximate the whole to a linear time-invariant (LTI) closed-loop system.

Consider a nonlinear time-variant (NLTV) system:

$$y = q(x) \;:\; N(y) = M(x) \qquad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

where $N \in \mathcal{N}$ and $M \in \mathcal{M}$, where $\mathcal{N}, \mathcal{M}$ are sets of nonlinear functions obtained by allowing the parameters to vary throughout their range.

Let there be a set $\mathcal{Y}$ of acceptable system outputs for the set of plants $\mathcal{Q}$ in response to a set $\mathcal{R} = \{r\}$ of closed-loop system inputs such that:

$$y \in \mathcal{Y} \quad : \text{ for all } q \in \mathcal{Q} \qquad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

This is achieved by requiring the closed-loop system to behave as a member of a desirable set $\mathcal{T}$ of LTI functions:

$$y(s) \triangleq T(s)r(s) \;:\; T(s) \in \mathcal{T}(s) \qquad \ldots\ldots\ldots \quad (9)$$

The set $\mathcal{T}$ is found by conventional methods by suitable tolerancing of the parameters of $T(s)$. Now to convert from NLTV to LTI, define a nominal output y_o by selection of the nominal N and M such that:

$$y_o = h * u = v \;:\; q = q_o \qquad \ldots\ldots\ldots\ldots\ldots \quad (10)$$

where * indicates convolution such that $h(t)$ is defined by $h = \mathcal{L}^{-1}H(s)$ and where $H(s)$ is the desired LTI plant function after the nonlinear compensation.

Now construct a cancellation function:

$$x \triangleq \Lambda(v) \;:\; N_o(v) = M_o(v) \qquad \ldots\ldots\ldots\ldots \quad (11)$$

In essence, a model following system has been defined with $y(t)$ following $v(t)$ exactly whenever the plant assumes its nominal form, with the nonlinearities of q being compensated for by those of Λ. The modified plant is therefore as shown in figure (6). This modification thus shows variations from $H(s)$ only if the parameters of the NLTV plant change and not because of the nonlinearities themselves. We now have:

$$\frac{y}{u}(s) = p(s) \;:\; p \in \mathcal{P} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

The extent of the set $\mathcal{P}$ must now be found before proceeding on the basis of a LTI sensitivity design (1,11). To do this, the known members of the set $\{y\}$ are substituted into equation (13) which is solved numerically for $v(t)$ and $v(j\omega)$.

$$N(y) = M(N_0 v)$$

$$\mathcal{P} = \left\{\frac{y(j\omega)}{v(j\omega)}\right\}.H(j\omega) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

The advantage of the method is that, for a large class of nonlinear systems, the cost of feedback can be reduced greatly since, in the absence of uncertainty, there is no need for the provision of feedback to handle the vagaries of the non-linear behaviour. That is, the modified plant behaves as if it were LTI for the specified set of system inputs and feedback is introduced only to limit the effects of the variation of the coefficients of the N and M polynomials (12,13).

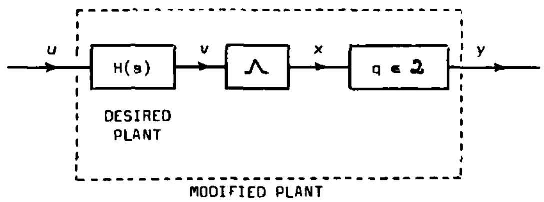


Fig (6): Nonlinear cancellation compensation to limit the variability of the effective plant prior to LTI design.

THE NONLINEAR MODEL

To proceed with the method of the previous section it is necessary to define a nonlinear representation of the ship's dynamics in order to formulate the cancellation compensation Λ. The Abkowitz formulation (14) is well known but, besides being too complex for hardware implementation, requires knowledge of all the variables of motion and the associated hydrodynamic derivatives. For these reasons it was the intention of the authors, certainly in the initial stages of the investigation, to examine the possibility of using only that information which could be obtained from standard ship trials such as the time variation of yaw rate on application of a constant rudder demand and the steady-state results of the spiral test. This would inevitably involve a loss of information and consequently a reduction in the ability of the model to predict the actual performance of the ship. However, it is considered that such a deficiency might be overcome by a slight change in the philosophy of the previous section whereby the uncertainty referred to arises from ignorance of the process rather than ignorance of parametric values.

Using common nomenclature the yaw equation of motion is given by:

$$I_z\dot{r} + mx_G(\dot{v} + ru) = N \qquad \ldots\ldots\ldots\ldots\ldots \quad (14)$$

where, on the Abkowitz representation, N is a function of odd powers of r and v and where, to a reasonable degree of accuracy (15), no rates of change of rudder angle are involved.

On application of a constant rudder demand the ship will yaw until, in the steady-state, the second derivatives of yaw and sway will reach zero when the ship will be moving in a circle at a constant yaw rate determined by the magnitude of the rudder demand. The RHS of equation (14) can be rewritten as:

$$N = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + mx_G ru + f \qquad \ldots\ldots\ldots\ldots \quad (15)$$

On substitution into equation (14) we have:

$$(I_z - N_{\dot{r}})\dot{r} + (mx_G - N_{\dot{v}})\dot{v} = f \quad \ldots\ldots\ldots \quad (16)$$

Thus, in the steady state the RHS of equation (16) can be equated to zero and will express the relationship between the steady-state values of yaw and sway rate and the rudder angle which themselves define the steady-state yawing moment acting on the ship from hydrodynamic sources. Thus, the drift angle β will increase until there is a balance between the effective turning moment due to the rudder and that due to the hydrodynamic effects when we will have:

$$f = N_\delta \underline{f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

where $\underline{f}$ is the effective rudder angle producing the turning moment.

The steady-state of equation (17) therefore expresses the relationship in polynomial form of the Dieudonne spiral curve in which the steady-state relationship between sway and yaw rate has been imbedded such that $\underline{f}$ is a function of only yaw rate and rudder angle. Let the spiral curve be approximated by:

$$\delta \simeq a_0 + a_1 r + a_2 r^3 \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

where a_0, a_1 are set to match the measured spiral curve at zero yaw rate and a_2 by its value at the maximum rudder angle.

The approximation is now introduced:

$$f \simeq N_\delta \underline{f} = N_\delta(\delta - a_0 - a_1 r - a_2 r^3) \quad (19)$$

To make use of equation (16) to formulate a yaw-rate/rudder-angle model it is necessary to eliminate v by invoking the relationship between v and r which, from the linearized equations of motion, is readily shown to be:

$$v = K. \frac{(1 + Ts)}{(1 + T's)}.r \quad \ldots\ldots\ldots\ldots\ldots \quad (20)$$

where the gain K and time constants T,T' will vary according to speed and the changing hydrodynamic derivatives.

The combination of equations (16,19,20) thus reveal the model to be basically of second order in its linear dynamics and of first-order in its nonlinear drive.

THE DESIGN APPROACH UNDER INVESTIGATION

The proposed model of the previous section is seen to include not only the steady-state spiral curve as required but also the linear dynamics which are defined in terms of the unknown or uncertain hydrodynamic derivatives. (Dimensionalisation will introduce speed as a variable). If, as is the intention, reliance is not to be placed upon knowledge of the derivatives, then the dynamics must be estimated from the measured response of the ship to constant rudder demands with due allowance for speed normalization. However it is notoriously difficult to carry this out in practice as a consequence of the sea-state noise which heavily contaminates the yaw rate signal and as a result of the overwhelming dominance of the response by the cubic nonlinearity (the linearized steady-state prediction of yaw rate can be as much as six times that actually achieved). The approach to be adopted, which is currently under investigation, is therefore:

(1) To assume that the measured response corresponds to a nonlinear model having the form:

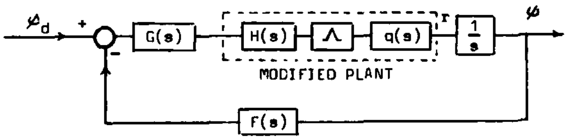
$$A(\frac{d}{dt})r(t) = -KB(\frac{d}{dt})\delta + C(\frac{d}{dt})r^3(t) \quad \ldots\ldots \quad (21)$$

where A,B and C are polynomials in the d/dt operator.

The polynomials are then determined to achieve a satisfactory match over the range of rudder demands. Note that because of the approximation of equation (19), to introduce the spiral curve, the terms of polynomial A will only approximate to the true linear dynamics.

(2) Using the model of equation (21) to deduce the inverse nonlinear compensation Λ of figure (6) and, on specification of a desirable set of dynamics for the ship defined by H(s), to follow the method as discussed to arrive at the modified plant set $\mathcal{P}$.

(3) Finally, bearing in mind the range of variation described by $\mathcal{P}$, to employ the method of sensitivity design (1,2,11) to achieve the set of transient response sensitivity specifications which will allow adequately repeatable manoeuvres. Thus, the formulation of the loop function L(s) of figure (7) will determine the insensitivity of the closed-loop system to the variation of the ship dynamics, whilst its distribution as G(s) and F(s) will permit authority over the closed-loop response.



Fig(7): Two degree-of-freedom yaw control system for simultaneous satisfaction of sensitivity and response specifications.

CONCLUSIONS

The reduction of the variation between the normalized responses of a ship to rudder demands of varying magnitude necessitates a loop bandwidth of such a range as to include the spectrum of sea-state noise with the consequent saturation of the rudder servo for any but the slightest sea motion.

Two means have been suggested whereby sensitivity reduction demands can be relaxed so as to bring about a reduction of the loop bandwidth. The first method, involving ship identification during the transients of the motion, proved to be of little assistance. It was found that the vessel was entering the steady state before the estimation algorithm had improved upon the a priori knowledge.

The second suggestion, involving pseudo cancellation of the nonlinearities of the ship based upon steady-state behaviour, appears to be a profitable line for investigation which is currently in hand. Successful accomplishment of the modelling phase will lead directly to the application of familiar LTI sensitivity-design techniques.

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ADAPTATIVE AUTOPILOT BASED ON POLE ASSIGNEMENT

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ABSTRACT

The paper deals with the design of a robust adaptive autopilot for ships, in which the control law is derived assigning the closed-loop poles to prespecified locations.

The autopilot assumes an ARMA model to represent the ship dynamics under environmental disturbances, the appropriate controller parameters being synthesized at each sample interval following a recursive identification process. Some criteria about the choice of the closed-loop pole locations are outlined.

The behavior of the autopilot has been studied by simulation using a non-linear model for a 356.000 tdw. oil tanker. Further, the autopilot has been implemented in a Z-80 microprocessor and experimented on board of an oceanographic vessel. The paper compiles the main results obtained under different sea conditions in course-keeping and course-changing.

1.- INTRODUCTION

In the last years, a decisive shift from conventional analogue controllers to digital devices with some kind of adaptive behavior has been produced. That is the case in ship steering [1 to 3] where changes in environmental conditions (current, wind, waves) and operational conditions (speed, draught) greatly influence the ship dynamics, demanding the adjusment of the autopilot parameters to maintain a good performance.

An autopilot has two main functions:
- steady state course-keeping at a given reference heading.
- course-changing once a new reference heading has been selected.

Minimization of drag induced by the steering must be considered in course keeping mode. Koyama [4] and Norrbin [5] have shown that the average increase of propulsion losses depends on the mean square of heading error and rudder angle amplitude.

Concerning the course-changing mode, the transition from the previous reference heading to the new one should occur quickly, minimizing overshoots and undershoots.

Several methods of optimal adaptive control to design autopilots that minimize a cuadratic criterion in course keeping, such as minimum variance and generalized minimum variance have been proposed [6,7]

Such autopilots, showing good performance in course-keeping mode, must make use of an additional controller or schedule a variable heading setting point in course-changing mode. Further, difficulties can arise in non minimum-phase or unstable ship dynamic situations.

The autopilot proposed in this paper is based on the pole assignment self-tuning method, that alows the design of a robust, though non optimal, controller.

A suitable assignment of the closed-loop poles leads to a good behavior in course-keeping and course-changing including non minimum-phase and unstable ship situations.

The design of the adaptive autopilot is described in section 2. This section covers the ship model assumed, the pole-assignment control rule, the adaptive algorithm and some criteria to place the closed-loop poles.

Section 3 presents the main results obtained by simulation using the nonlinear model of a 356.000 tdw. tanker suggested by Kallstrom [8], in full load and ballast conditions. The implementation of the controller to the oceanographic vessel BANNOCK and the experiments performed jointly by the Istituto per l'Automazione Navale (Genova) and the Institut de Cibernética (Barcelona), during a mediterranean voyage in December 1.980, are also summarized in this section.

Finally, the major conclusions are given in Section 4.

2.- ADAPTIVE AUTOPILOT DESIGN

2.1-Ship Model

The equations describing the horizontal plane motion of a ship are obtained from the conservation of linear and angular momentum:

$$
\begin{aligned}
m(\dot{u} - v.r - x_G . r^2) &= X \\
m(\dot{v} + u.r + x_G . \dot{r}) &= Y \qquad (1) \\
I_Z . \dot{r} + m.x_G . (\dot{v} + u.r) &= N
\end{aligned}
$$

where X, Y and N are the forces and momentum exerted on the ship due to hydrodinamic and environmental conditions. These components are complex functions of the ship motion [12] but can be linearized around a steady state, that represents the normal situation of the autopilot operation.

The lineal model obtained after several simplifications without considering environmental disturbances, is called Nomoto's model (9), its transfer function being:

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{s(1+Ts)}$$

where ψ is the course of the ship and δ the rudder angle.

The dynamics of higher order and the time response of the steering gear is taken into account by adding a pure delay to the model:

$$\frac{\psi\ (s)}{\delta_c\ (s)} = \frac{K\ e^{-\tau\ s}}{s(1+Ts)} \tag{3}$$

δ_c is the setting point signal of the steering gear.

If this continous model is sampled with a sampling period h higher than the delay τ, will be obtained:

$$A(q^{-1})\ y(t) = B\ (q^{-1}\ )\ u(t) \tag{4}$$

where in general:

$$\begin{aligned} A(q^{-1}\ ) &= 1 + a_1\ q^{-1} + \ldots + a_{n_a}\ q^{-n_a} \\ B(q^{-1}\ ) &= b_1\ q^{-1} + \ldots + b_{n_b}\ q^{-n_b} \end{aligned} \tag{5}$$

being in this case:

$$y = \psi\ , \quad u = \delta_c\ , \quad n_a = 2 \quad \text{and} \quad n_b = 3$$

and the coefficients a_i, b_i are explicit functions of the parameters K, T and τ [8].

Åstrom [10] has proved that the essential features of most disturbances, can be described by:

$$\lambda\ \frac{C(q^{-1}\ )}{A(q^{-1}\ )}\ e(t) \tag{6}$$

where $A(q^{-1})$ and $C(q^{-1})$ are polynomials of second order ($n_c = n_a = 2$), $\{ e(t) \}$ is a non correlated normal random sequence and the parameter λ depends on the level of environmental disturbances.

So that, the complete model will be:

$$A(q^{-1})\ y(t) = B(q^{-1}\ )\ u(t) + \lambda\ C(q^{-1}\ )\ e\ (t) \tag{7}$$

This model describes the ship dynamics and the environmental disturbances by means of a simple structure very useful in adaptive autopilot design, based in the parameter estimation of the model in every instant of sample, in order to know the ship's behavior (Fig. 1).

2.2-Pole-Assignment Controller

The pole-assignment control law seeks to find the controller parameters in such a way that the prespecified closed-loop pole positions may be achieved. The controller experssion with a setting point course zero, can be writen:

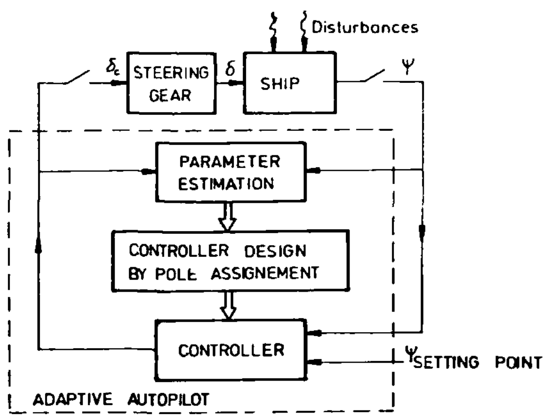

Figure 1.- Schema of a adaptive autopilot.

$$u(t) = -\frac{G(q^{-1})}{H(q^{-1})} \; y(t) \qquad (8)$$

Incorporating the control law (8) to the model (7), the following closed-loop system description is obtained:

$$y(t) = \lambda \frac{C(q^{-1}) \; . \; H(q^{-1})}{A(q^{-1}) \; . \; H(q^{-1}) + B(q^{-1}) \; . \; G(q^{-1})} \; e(t) \qquad (9)$$

the closed-loop poles will be shifted to the locations defined by $T(q^{-1})$ by setting the identity :

$$A(q^{-1}) \; . \; H(q^{-1}) + B(q^{-1}) \; . \; G(q^{-1}) = C(q^{-1}) \; . \; T(q^{-1}) \qquad (10)$$

Then, the closed-loop equation should be written:

$$y(t) = \lambda \frac{H \; (q^{-1})}{T(q^{-1})} \; e(t) \qquad (11)$$

For equation (10) to have a solution, the order of the controller polynomials must be:

$$\begin{aligned} n_G &= n_a - 1 \\ n_H &= n_b - 1 \end{aligned} \qquad (12)$$

the number of closed-loop poles n_t being limited by

$$n_t \leq n_a + n_b - n_c - 1 \qquad (13)$$

The general controller expression (8), in our case will be defined by:

$$H(q^{-1}) = 1 + h_1 q^{-1} + h_2 q^{-2}$$

$$G(q^{-1}) = g_0 + g_1 q^{-1} \qquad (14)$$

$$T(q^{-1}) = 1 + t_1 q^{-1} + t_2 q^{-2}$$

where the controller parameters (h_i , g_i) are linear functions of the model parameters (a_i , b_i , c_i) and the preselected closed-loop poles (t_i), throught the matrix equation:

$$\begin{bmatrix} h_1 \\ h_2 \\ g_0 \\ g_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & b_1 & 0 \\ a_1 & 1 & b_2 & b_1 \\ a_2 & a_1 & b_3 & b_2 \\ 0 & a_2 & 0 & b_3 \end{bmatrix}^{-1} \cdot \begin{bmatrix} -a_1 + c_1 + t_1 \\ -a_2 + c_2 + c_1 t_1 + t_2 \\ c_2 t_1 + c_1 t_2 \\ c_2 t_2 \end{bmatrix} \qquad (15)$$

To cover both course keeping and turning modes, it is possible to incorporate the reference heading signal y_c (t) by replacing the regulator (8) by

$$u(t) = - \frac{G(q^{-1})}{H(q^{-1})} \{ y(t) - y_c (t) \} \qquad (16)$$

The integrator assumed in the ship dynamic model should lead to steady-state correspondence with the reference input y_c (t).

2.3- Adaptative Autopilot Algorithm

The unbiased estimation of the model parameters (a_i , b_i , c_i) is a difficult real time task. Because of this, several authors have proposed model structures that alow easy parameter estimation, the controller parameters converging in probability to the actual ones, g_i , h_i , given by the matrix expresion (15) . In that sense for the design of pole-assignment self-tuning controller, Wellstead [11] has proposed a model with uncorrelated noise:

$$\mathcal{A}(q^{-1})\ y(t) = \mathcal{B}(q^{-1})\ u(t) + \lambda\ e(t) \qquad (17)$$

where

$$\mathcal{A}(q^{-1}) = 1 + \alpha_1 q^{-1} + \ldots + \alpha_{n_a} q^{-n_a}$$

$$\mathcal{B}(q^{-1}) = \beta_1 q^{-1} + \ldots + \beta_{n_a} q^{-n_a} \qquad (18)$$

the regulator parameters satisfaying the identity:

$$\mathcal{A}(q^{-1}) \cdot H(q^{-1}) + \mathcal{B}(q^{-1})\ G(q^{-1}) = T(q^{-1}) \qquad (19)$$

If the expression (19) is fulfiled and the system converges, it will converge to the desired closed-loop configuration, despite the incorrect assumption of uncorrelated noise.

The algorithm for the adaptive autopilote by pole-assignment will be as follows

Step 1 : At each sample interval, the parameters α_i and β_i of the model

$$y(t) = \underline{\psi}^T(t) \,.\, \underline{\theta}\,(t) + \lambda\, e(t) \tag{20}$$

with

$$\underline{\psi}^T(t) = \{ -y(t-1),\ -y(t-2),\ u(t-1),\ u(t-2),\ u(t-3)\} \tag{21}$$

$$\underline{\theta}^T(t) = \{ \alpha_1,\ \alpha_2,\ \beta_1,\ \beta_2,\ \beta_3 \} \tag{22}$$

are estimated by recursive least squares, described by the equations

$$\underline{\theta}\,(t+1) = \underline{\theta}(t) + \frac{P(t+1) \,.\, \underline{\psi}(t+1) \,.\, \{ y(t+1) - \underline{\theta}^T(t) \,.\, \underline{\psi}\,(t)\}}{\mu + \underline{\psi}^T(t+1) \,.\, P(t+1) \,.\, \underline{\psi}\,(t+1)} \tag{23}$$

$$P(t+1) = \{ P(t) - \frac{P(t) \,.\, \underline{\psi}(t) \,.\, \underline{\psi}^T(t) \,.\, P(t)}{\mu + \underline{\psi}^T(t) \,.\, P(t) \,.\, \underline{\psi}(t)} \} \,/\, \mu \tag{24}$$

where μ is a forgetting factor, in order to track slow changes of the parameters.

Step 2 : The regulator is syntherized, calculating the parameters by the matrix expression:

$$\begin{bmatrix} h_1 \\ h_2 \\ g_0 \\ g_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & \beta_1 & 0 \\ \alpha_1 & 1 & \beta_2 & \beta_1 \\ \alpha_2 & \alpha_1 & \beta_3 & \beta_2 \\ 0 & \alpha_2 & 0 & \beta_3 \end{bmatrix}^{-1} \begin{bmatrix} t_1 - \alpha_1 \\ t_2 - \alpha_2 \\ 0 \\ 0 \end{bmatrix} \tag{25}$$

Step 3 : The rudder control signal is then obtained by means of

$$u(t) = - \Big[g_0 \,\{y(t) - y_c\} + g_1\{ y(t-1) - y_c\} + h_1\, u(t-1) + h_2\, u(t-2) \Big] \tag{26}$$

Step 1, 2 and 3 are repeated at each sample interval.

2.4-Pole Location Criteria

In order to implement the adaptive autopilot algorithm, the closed-loop pole locations must be predefined. Although a general rule does not exist at present , some criteria can be given, as a guide to select pole locations leading to good autopilot performances.

A rather simple pole assignment law has been established assuming that all closed-loop poles are placed at a single point, z_0 , located on the positive portion of the real axis contained within the unit circle of the - - plane :

$$T(z^{-1}) = (1 - z_0\, z^{-1})^2 \tag{27}$$

with

$$0 \leq z_0 < 1$$

Heading deviation and rudder angle in course keeping-mode will be given by

$$y(t) = \lambda \frac{H(q^{-1})}{T(q^{-1})} e(t)$$

$$u(t) = \lambda \frac{G(q^{-1})}{T(q^{-1})} e(t) \qquad (28)$$

The loss function to be minimized in course keeping mode is:

$$J = E\{ y^2(t) + \rho u^2(t) \} \qquad (29)$$

In our case, the input and output variances, will be calculated from the expressions:

$$E\{u^2(t)\} = \lambda^2 \{g_0^2 + (g_1 + 2z_0 g_0)^2 + \sum_{i=3}^{\infty} z_0^{2(i-2)} \cdot [(i-1) g_1 + i z_0 g_0]^2 \}$$

$$E\{y(t)\} = \lambda^2 \{1 + (h_1 + 2z_0)^2 + (h_2 + 2z_0 h_1 + 3z_0^2)^2 + \sum_{i=4}^{\infty} z_0^{2(i-3)} \cdot [(i-2)h_2 + (i-1)z_0 h_1 + iz_0^2]^2 \} \qquad (30)$$

In particular, for $z_0 = o$, these expressions are reduced to

$$E\{u(t)\} = \lambda^2 (g_0^2 + g_1^2)$$

$$E\{y(t)\} = \lambda^2 (1 + h_1^2 + h_2^2) \qquad (31)$$

Showing that the input and output variances depends linearly on the square value of the controller parameters (h_i, g_i). The expression (31) can be assumed to hold for non-zero values of z_0 sufficiently close to the origin of the z-plane.

On the other hand, the controller parameters are only affected explicitly by the closed-loop poles position, z_0, through the vector:

$$\underline{\gamma}^T = [-\alpha_1 - 2z_0, -\alpha_2 + z_0^2, 0, 0] \qquad (32)$$

Then, for habitual values of α_1 and α_2, the controller parameters will have opposite signs for $z_0 < \sqrt{\alpha_2}$ and $z_0 > |\frac{\alpha_1}{2}|$, and one possible solution to poles location would be to preselect a value of z inside the unit circle and slightly smaller than $\sqrt{\alpha_2}$. That will lead to small numeric values of the input and output variances.

In course-changing mode, the mean square rudder angle in the loss function is not weighted, and a location of z_0 near the origin of the z-plane will lead to a quick heading transition with low overshoot and undershoot.

3.- IMPLEMENTATIONS AND RESULTS

Two ways have been used to validate the design of the adaptive autopilot algorithm.

First, it has been applied to a nonlinears model of a supertank through simulation in a digital computer. Second, it has been implemented on board of an oceanographic vessel during an experimental sea voyage. The results obtained are described in the following subsections.

3.1- Simulation results

The non-linear model of the ship has been simulated in a SEL 32/77, using the Block CSMP language. The equations of motion characterizing the model (7) contain the hydrodynamic forces X and Y, and the hydrodynamic moment N defined by Norrbin [12].

The parameter values for the supertank "Sea Stratus" have been estimated under different operational and environmental conditions by Kallstron and co-workers [13].

A summary of those conditions is shown in Table I:

Supertank load	Mean speed	current		wind		waves	
		speed	direction	speed	direct.	height	direct.
fully laden	15.8 knots	0.5 m/s	45 °	10 m/s	45 °	3 m	45 °
ballast	17 knots.	0.5 m/s	210 °	15 m/s	210 °	5 m	210 °

<u>Trial 1</u>

Figures 2,3 and 4 show the results obtained when z_0 takes the values : 0.4, 0.6 and 0.8. During the first 1.000 seconds, the ship is mantained in course-keeping mode. After this period of time, a turning of 10°is applied.

The transient time elapsed during the course-changing operation depends on the pole positions; the closer to the origin, the better the response obtained (less duration and less overshoot). This is attained by means of a strong rudder action. The mean square deviations of heading and rudder for different pole positions, while operating in 0°course-keeping, are displayed in figure 5.

As it can be easily seen, the best results in course-keeping are for z_0 in the interval (0.6 , 0.8), depending on the numeric value of the weighting factor ρ in the criterium. The results are quite different in course-changing mode, where a value of $z_0<0.4$ produces a fast response with a satisfactory overshoot.

The steady state value of the parameters of the adaptive controller (g_i,h_i) in course-keeping decreases continuosly in absolute value as the position of z_0 increases (table II), thus corroborating what was said in subsection 2.4.

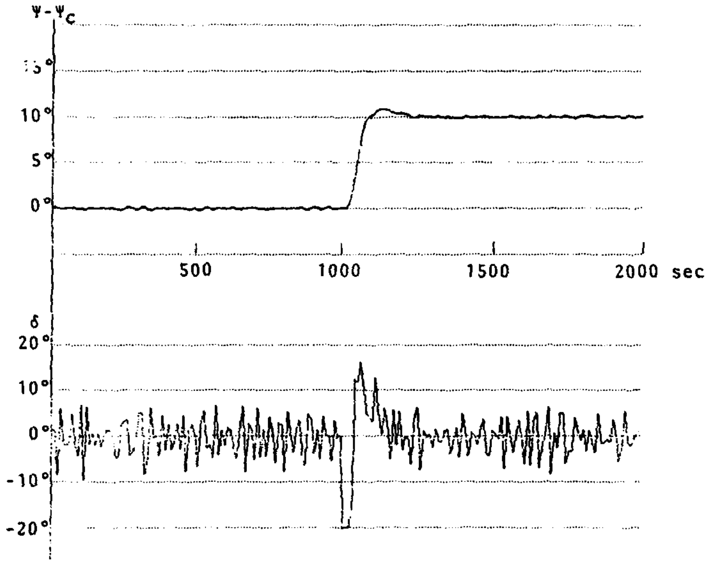

Figure 2.-Results in full-load condition for z_0=0.4

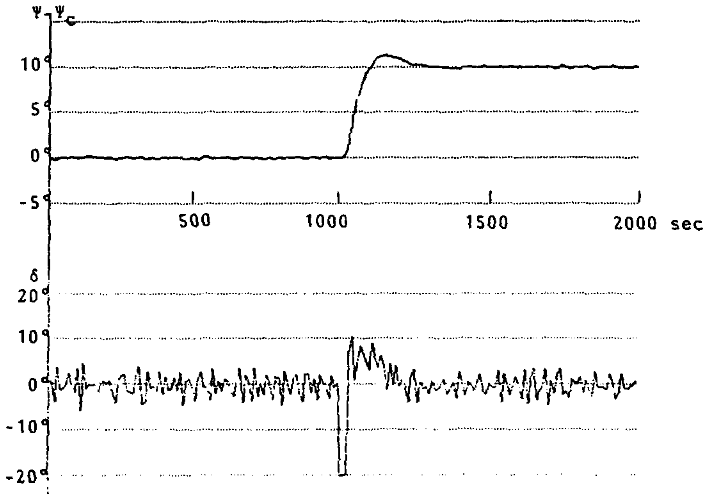

Figure 3.- Results in full-load condition for z_e=0.6

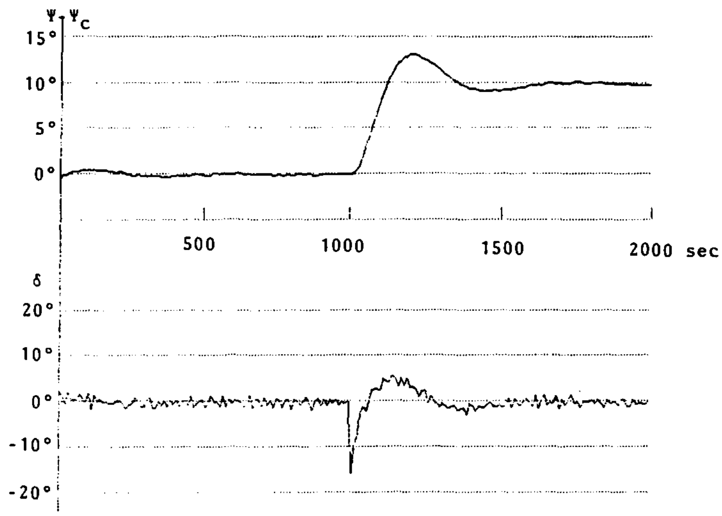

Figure 4.- Results in full-load condition for z =0.8

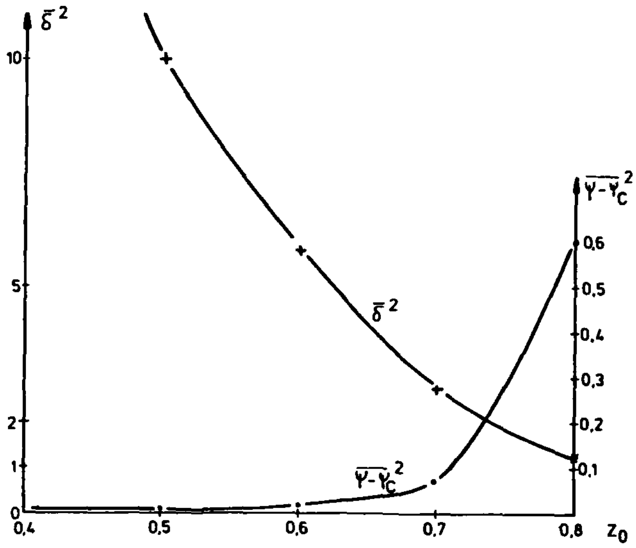

Figure 5.- Input and output variances in full-load condition

z_0	g_0	g_1	h_1	h_2
0.4	-32.	23.	0.5	0.07
0.5	-27.	20.	0.4	0.07
0.6	-21.	17.	0.4	0.09
0.7	-16.	13.	0.3	0.09
0.8	-10.	9.	0.2	0.06

Table II. The steady state value of the parameters of the controller

The value of z_0 should not exceed 0.8 in both, turning and course keeping modes,in order to stay away enough from the unstable region.

Trial 2. The results corresponding to the ballasted tanker in course-keeping and course-changing (0°, +10°, 0°) for z_0 equal to 0.2, 0.3 and 0.4, are shown in figures 6, 7 and 8. The input and output variances as a function of z_0 in 0° course-keeping are displayed in figure 9.

As it can be seen in figure 9, a satisfactory behaviour is obtained for z_0 comprised in the interval (0.4, 0.6). The transient response in ballast condition is however slightly worst that in full load condition for the same values of z_0.

Table III summarizes the steady state values of the control parameters for several values of z_0. A change in sign of some parameters can be observed for z_0 beyond 0.6. Therefore according to the pole location criteria in subsection 2.4, z_0 should be selected with a value slightly smaller than 0.6, in course-keeping. The simulation results (figure 9), confirm this criterium.

z_0	g_0	g_1	h_1	h_2
0.2	-10.	3.5	0.5	0.7
0.4	-3.	0.2	0.1	0.5
0.6	-0.4	-0.7	-0.6	0.4
0.8	0.1	-0.4	-0.8	0.3

Table III. The steady state value of the parameters of the controller in ballast condition.

3.2- Experimental Results

A set of experiments hes been carried out on board of an italian oceanographic research vessel, the Bannock, during a voyage between Elba Island and Genova(Italy) in december 1980. The Bannock is 62m long, weighs 1300 tons and has a nominal speed of 10 knots.

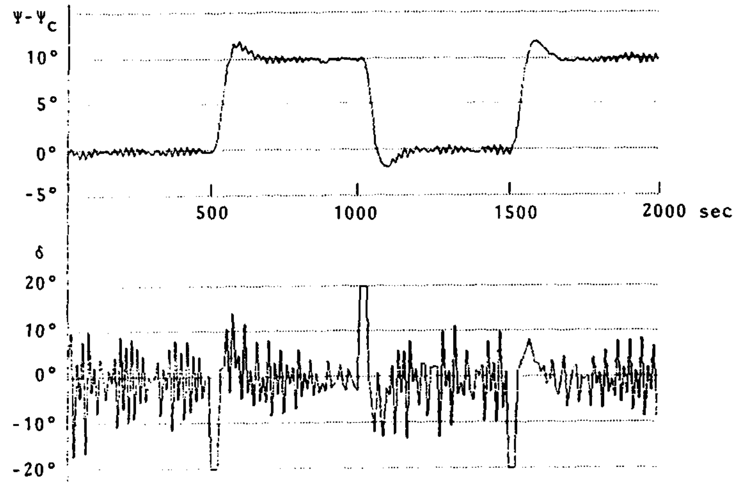

Figure 6.- Results in ballast condition for z_e=0.2

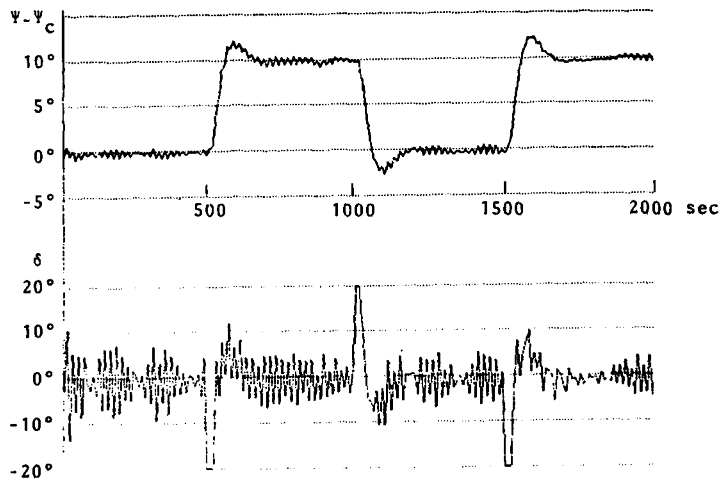

Figure 7.- Results in ballast condition for z_e=0.3

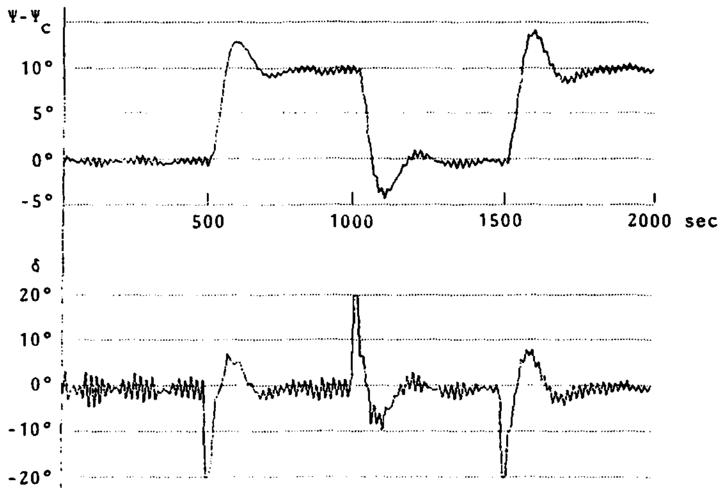

Figure 8.- Results in ballast condition for z_0=0.4

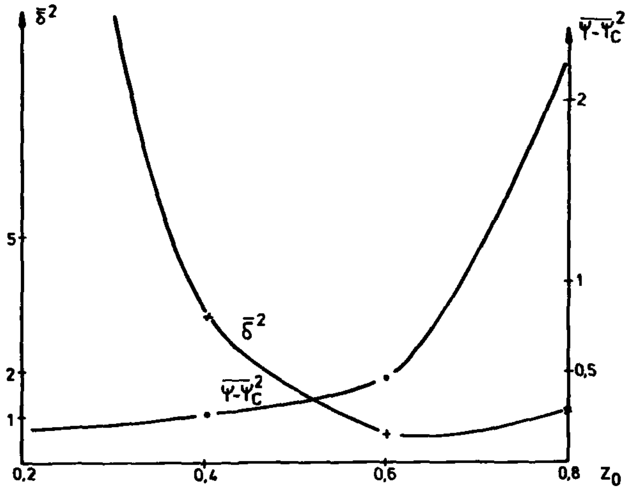

Figure 9.- Input and output variances in ballast condition

The adaptive autopilot algorithm has been implemented in a ZILOG Z-80 microprocessor on board of the vessel. Its main configuration is:

- 64k byte memory
- 32 analog inputs
- 4 analog outputs
- 2 floppy disk drivers, single density
- operator console

The rudder position control and the girocompass are interfaced to the microprocessor.

The operational and environmental conditions during the course-keeping test of the adaptive autopilot have been:

vessel speed: 9.2 knots
setting-point course: 25°
wind speed: 15 m/sec
wind direction: 315°

The sampling interval was fixed to 4 seconds and several values of z_0 have been used (figure 11).

The change of the sign of the controller parameters appeared in the interval (0.6, 0.7) of z_0. Figure 11 shows that the best value of z_0 is close to 0.5.

In course-changing mode, a set of experiments were performed selecting different steps of the setting-point course (10°, 20°and 100°) and several values of z_0. The maximum angle rudder was limited to 10°. Figure 10 shows the transition heading angle corresponding to a variation of 100° in the reference heading, for z_0 equal to 0.5, the undershoot and overshoot obtained being quite admissible..

4.- CONCLUSIONS

An adaptive autopilot based on pole assignment and making use of a simple model to represent ship dynamics and environmental disturbances, has been designed. The method could be applied to more complex models, but the results obtained show that rather good performance is achieved with the proposed autopilot.

The adaptive autopilot obtained presents a robust behaviour and it is able to work properly in non-minimum phase and unstable ship dynamic situations. Further, it allows to cover the two autopilot modes: course-keeping and turning.

The design of the autopilot requires previous closed-loop pole location specification. In that sense, the results obtained from simulation and experimentation confirm that the double closed-loop pole should be near the z-plane origin in order to have proper heading transition in course-changing mode, besides the great rudder deviation required.

In course-keeping mode, the performance of the autopilot is not far from the optimal one if the double closed-loop pole is located in the neighbourhood of the sign change interval of the regulator parameters.

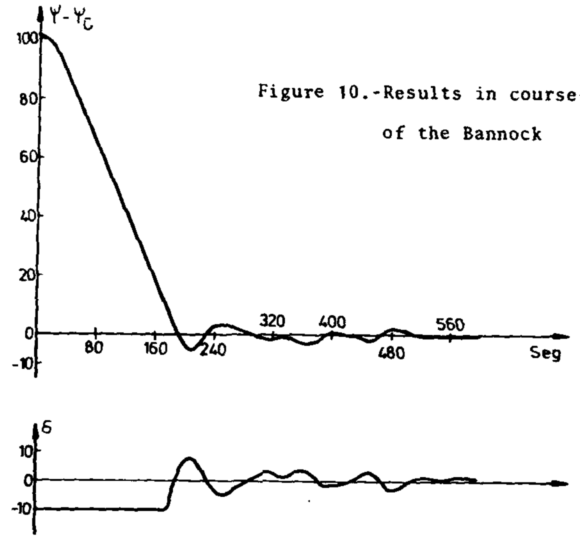

Figure 10.-Results in course-changing of the Bannock

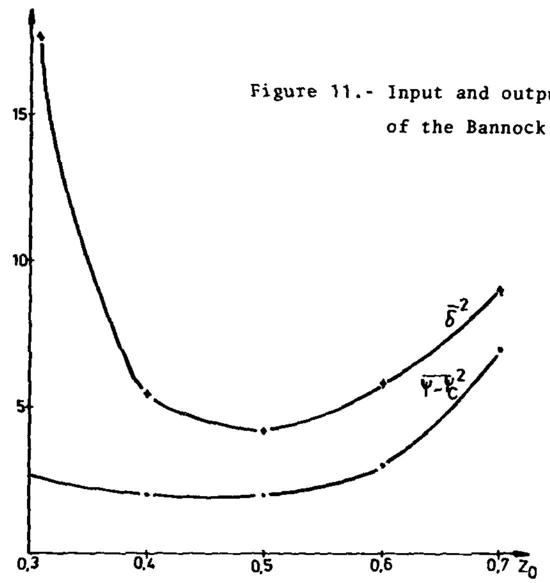

Figure 11.- Input and output variances of the Bannock

A more detailed study including sensitivity analysis of closed-loop pole positions and experimental comparison with other adaptive autopilots will be carried out in the next future.

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